UNIVERSITY OF EDINBURGH

THE DRAUGHT, TORQUE AND POWER REQUIREMENTS OF SIMPLE VIBRATORY TILLAGE TOOLS FOR TWO AGRICULTURAL SOILS

by

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Dedicated

to

Davena, Jeff and Leslie

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ABSTRACT OF THESIS

The method used to investigate vibratory tillage was a factorial experiment. It was argued that an analytical study was not feasible at the time and, though dimensional analysis was another alternative, only the draught could be related to the other variables.

The factors included in the experiment were argued with reference to the results obtained by other investigators. The draught and drawbar horsepower, the torque and shaft horsepower and the total horsepower were determined for the independent factors of frequency, amplitude and the plane of oscillation of the tool, the tool rake angle and two soil factors; texture and density.

The experiment was conducted using simple tillage tools in two agricultural soils which were remoulded in a tank. The first part of the experiment explored the variations in the soil resistance within and between soil preparations. Variations in the soil resistance across the tank necessitated a special experimental design for efficient use of time and material for the second part of the experiment.

The soil pF-moisture content relationship was determined so that the two soils might have the same pF. Laboratory compaction tests were conducted as an aid in specifying the appropriate compacting procedures for the soil tank. Even so, extensive compaction trials were required. As part of this work the correlation between the bulk density and the soil resistance of a cone penetrometer was determined.

The plots within the tank were prepared with a special plough. Much of the heterogeneity of the residual variance that was experienced was attributed to the inability of the plough to maintain a constant plot width

in one of the dense soils. Variations in the vibratory drive friction required a study in order to estimate the torque associated with tilling of the soil.

The basic objective of the investigation was to increase the energy efficiency of the tillage process. It was argued that this objective might be achieved using vibratory tillage for large cultivating units in dense soil. The main advantage, however, would be in preventing detrimental levels of mechanical impedance from occurring in the traffic sole.

All vibratory tillage studies have noted that the draught of a vibrating tool was less, sometimes substantially less, than the draught of a rigid tool. Some of the studies reported a decrease in the total power requirements while others reported an increase. It was argued that some of the difference in the total power may have occurred because the minimum drawbar horsepower does not coincide with the minimum total power requirements and that the shaft horsepower is independent of the soil density.

Some of the results were similar to those of other studies, but there were a number of exceptions. It was argued that the reduction in the draught and drawbar horsepower for vibratory tillage might be the result of fluidization of the soil. Interactions indicate that the factors of amplitude and plane of oscillation are not independent of the other factors and that the relationships are complex.

CHAPTER 1

INTRODUCTION

Agriculture is the basis of man's civilized society. Whether the present society is "good" or even "just" is being questioned today, sometimes violently. The questions and the answers are important, but not of interest here. What is pertinent is that such a debate could not take place without an efficient agricultural base. Only when the concern for survival is far removed, can the broader question of a "good" and "just" society be entertained. In a sense the debate is a measure of the efficiency of agriculture. The conventional "yardstick" for agricultural efficiency, however, is the farm production per worker.

The rapid decrease in the farm population over the past two decades is inversely related to a large increase in farm mechanization. From horses to tractors; from reapers to combines; production per agricultural worker has risen dramatically. Unfortunately these statistics obscure the fact that there has been a large transfer of the labour cost to the operating and fixed costs. If the relative costs of farm production have decreased much in this period, it must be due to other factors and not to the level of mechanization. As evidence, Wendell and Bateman (94) in 1960 wrote, ".... increased tillage was brought about by the development of larger equipment that would cover the ground faster. Farmers would then use the time saved to make more trips, believing that more tillage insured a better seed bed." On the other hand, tillage studies indicate that less tillage, rather than more, is beneficial. Coincidental with this activity was the development of herbicides so that it was possible for Elliott (30) to suggest in 1967 that for cereals zero tillage would be realistic, if it was not for wheel tracks from harvesting equipment. In zero tillage, the only required soil disturbance would be for spot placement of the seed. Elliott may be over-optimistic. In the first place, there is an increasing concern about the "side-effects" of pesticides and herbicides. In the second place, there is a transfer of chemical costs for tillage costs without much or any reduction in the production costs. It would seem that tillage will still be a major activity of farming and that efforts to increase tillage efficiency should be continued.

Tillage is a major expense in farming. The farmers in the Province of Alberta, Canada,* for example, have invested 19% of their total machinery investment in cultivation equipment (2). This statistic grossly understates the magnitude of their investment as the greater part of their power investment is associated with tillage. The relationship of these investments to other machinery investments is illustrated in Figure 1 top. A better estimate of tillage costs to Alberta farmers (3) is found in Figure 1 btm. Even the lowest estimate (Zone 2) is impressive. Assuming that this brief appraisal is sufficient for the continuation of tillage research, the question arises as to who should conduct such studies.

Agriculture, like the other sciences, has divided itself into a number of disciplines with further divisions of specialization until it is now difficult to record them all. This proliferation is the result of the need to specialize, for without it, the complex relations of this mechanical world

* This area was chosen because of its familiarity to the author. The area represents a relatively high level of mechanization with the broad spectrum of farming enterprises usually found in the temperate zones of the world.

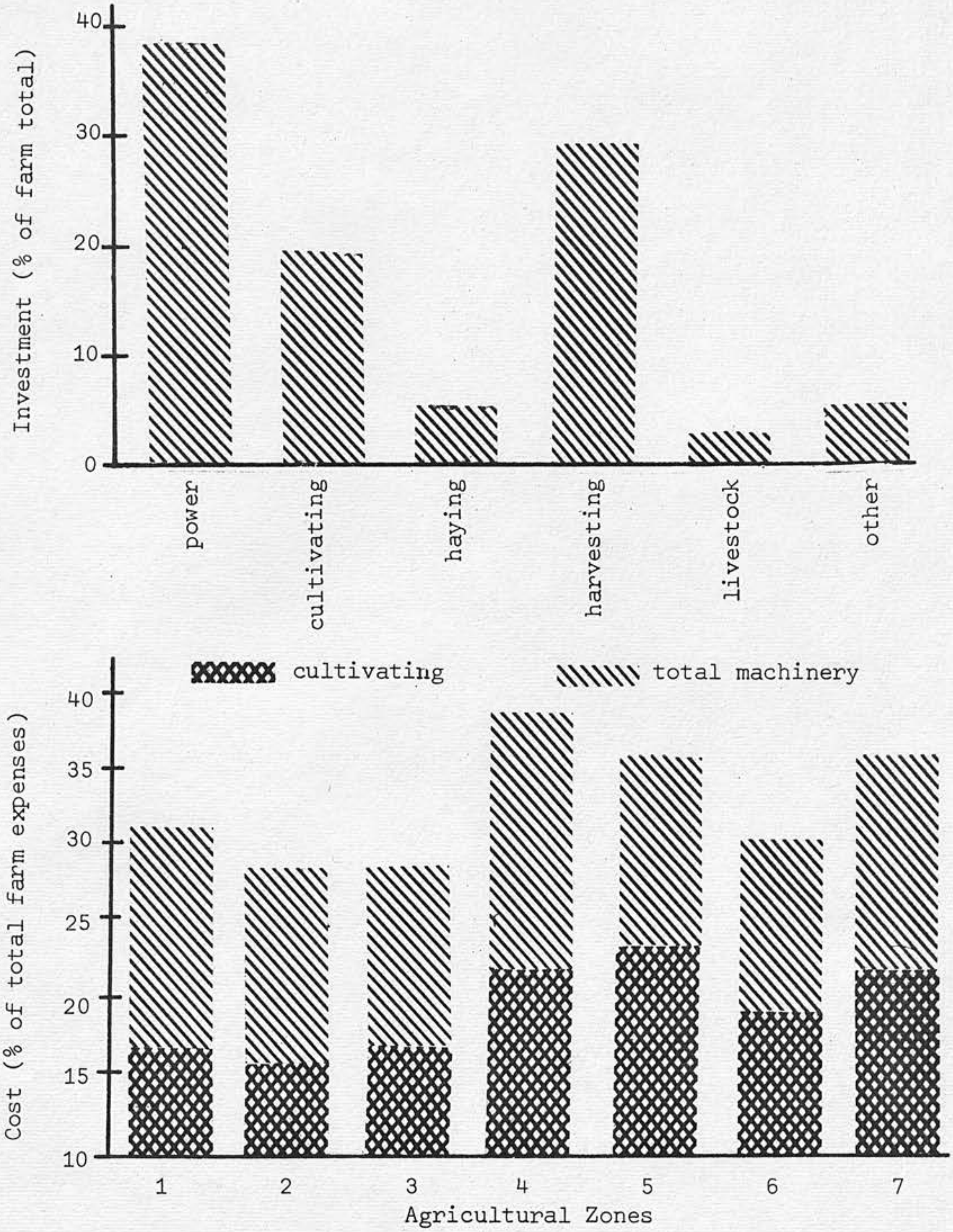

Figure 1 Farm Machinery Investment (top) and Production Expenses (btm) for the Province of Alberta, Canada.

cannot be fathomed. In some instances the area of specialization of one discipline has impinged on one or more areas of specialization of other disciplines. An example occurs with the interest of the soil physicist, the agricultural engineer, and to a lesser extent, the civil engineer in tillage. It can be argued that tillage research should involve all three specialists. Though there are examples of this involvement, they are few in number. The main difficulty seems to be the lack of common interest in any one research institute. As a result, the bulk of the tillage studies has been conducted by the agricultural engineer. He has one advantage and that is his greater awareness of the other two disciplines. In vibratory tillage studies, this advantage is accentuated because of his awareness of the mechanics of motion; normally the domain of the mechanical engineer.

Having briefly observed the "why" of tillage research and the "who" of the researcher, it is useful to similarly explore the "how". Hiebert (47) declares that we can "change the course of events to our advantage providing always that we wedge our purposes into the system at the proper space and time intervals." For this we need the "descriptions of the functional relationships of one part of the system to another part." The relationship we seek is "the time order which assigns A as the cause of B, B as the cause of C and so forth, ...". The description of these relationships are to be found by "cutting our experiences into stove lengths so that we can handle them better." The first set of "stove lengths" is the agronomic requirements of tillage.

CHAPTER 2

AGRONOMIC REQUIREMENTS

Introduction

Soil cultivation is an ancient art dating from the time that man changed his society from hunting to agricultural. In the interval to the present, three basic tillage tools have evolved. They differ from each other in the extent to which the soil is inverted. They are:

mould-board plough	- complete inversion,
disk (disk plough)	- partial inversion,
inclined blade (sweep, shovel, tine)	- no inversion.

Strictly speaking, some soil inversion occurs with the last and the amount may be significant in the case of a tine. The degree of soil inversion has important effects on disease and insect control, soil erosion by wind and water, and soil temperature. Some of these are conflicting requirements. For example, complete inversion is useful for disease and insect control, but is a hazardous tillage practice in areas subject to wind and water erosion. In spite of its importance, this aspect of tillage is omitted in order to concentrate on the primary result of tillage which is the pulverization of the soil. Pulverization, for the purpose of this review, is defined as a loosening of the soil with an increase in pore space and comminution of the soil aggregates. Compaction is not included in the definition although many authorities would do so.

In general, the function of agricultural soils is to supply nutrients to the plant and provide for its mechanical support (61). It is a mixture of mineral materials, organic matter, water and air. The composition of these constituents for optimum growth for higher plants (in silt loam), according to Buckman and Brady (15), is:

```
                  (45% minerals
50% solids      - (
                  ( 5 % organic

                  (25% water
50% pore space  - (
                  (25% air
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The effect of tillage with respect to these constituents would appear to be limited to the manipulation of the pore space. The agronomic requirement of the soil pulverization process, however, is more complex than this.

Weed and erosion control, according to Buckman and Brady (15), are two important functions of tillage. Inversion of the soil furrow is the most effective means to eradicate weeds. They may be, however, sucessfully extirpated by the soil pulverization process alone if the stage of growth and the soil moisture fall within certain ranges. For example, to eradicate weeds in the seedling stage, the soil would have to be dry or excessive comminution of the soil clods would be required. With loosening of the soil, control of soil erosion by wind can often be obtained as observed by Lyles and Woodruff (60). Increasing the number and size of surface clods by the tillage process reduces the wind velocity in the critical boundary zone. The hazard of soil erosion by water can be reduced slightly with an increase in surface clods, but the main benefit, according to Arndt and Rose (4), is an increase in the infiltration rate. The magnitude of the surface run-off is inversely related to the infiltration rate.

Less obvious, but a vital factor in the soil-plant interface, is the degree of pulverization and the amount of change in pore space resulting from tillage. Shaw (77) asserts that there are four physical (edaphic) factors with regard to plant growth in which pulverization has a minor role.

They are:

- moisture,
- aeration,
- temperature,
- mechanical impedance.

Soane (81) appears to have these factors in mind when he wrote, "Understanding of the mechanisms by which tillage practices affect crop growth and yield will be successful only if soil physical properties of direct and proven relevance are measured ....." He argues that yield has limited usefulness as an assessment of tillage effects. Although this seems to be the logical conclusion from the evidence he submits, it does not appear to simplify the difficulty. Gill and Miller (36) have commented, "The physical properties of the soil which influence the behaviour of plants are relatively few, but their interactions are so complex as to make it almost impossible to reach quantitative conclusions with respect to the significance of the individual factors." In view of this, and the foregoing, the remainder of the review on the agronomic requirements will be largely restricted to the main effects of the four edaphic factors as they relate to the soil pulverization process of tillage.

Soil Moisture

Richards and Wadleigh (69) assert that soil moisture is directly and indirectly related to plant growth. The direct effects have reference to the availability of water for plant growth. They state that for sub-humid climates, soil moisture supply is the most critical factor in crop production. The indirect effects pertain to the relationship of soil moisture and the other edaphic factors of aeration, temperature and mechanical impedance. Both effects are related to the soil permeability which, on the one hand governs the gain of water by infiltration and, on the other, the loss by percolation. Surface evaporation is the other important loss of water from the soil. In order to minimize evaporation, Holmes et al. (40) found that a "fine tilth consisting largely of soil crumbs with a diameter of 2.5 mm was the most effective."

Richards and Wadleigh (69) allege that the transmission velocity of water in the soil differs depending on whether it is a saturated or unsaturated flow, which, in turn, is affected by the permeability of the soil. For example, if the soil permeability is uniform, there is a reduction in the transmission velocity with a transition from saturated to unsaturated flow. A reduction in the transmission velocity will also occur with a converse transition of flow from unsaturated to saturated if the permeability decreases with depth. According to Richards and Wadleigh (69), Richards and Lamb (1957) have observed temporary or perched water tables with the low permeability of hard pans or plough soles.

Buckman and Brady (15) state that permeability is a function of the soil structure and texture. Browning (14) declares that tillage can modify the structure, but its effectiveness is dependent on other factors such as the amount of organic matter and the soil moisture at the time of tillage. With regard to plough or traffic soles, Soane's (81) conclusion is relevant, "The depth of compaction during the passage of tractor wheels exceeded the depth of penetration of most secondary cultivation implements." It would appear from this that the advantages of increasing the surface permeability or infiltration rate by tillage is offset, to a degree, by a decrease below the tilled depth.

The flow and distribution of water in the soil is altered by the plant which in turn differs for an established root system and one that is developing. Plant roots can create large hydraulic gradients and because of capillarity, water will move toward them. Lyon and Buckman (61) wrote, "... capillarity, although it may act through a distance of several feet, if time be given, may actually be of importance through only a few centimeters as far as the hour by hour needs of the plant are concerned." This may be adequate for plants with an established root system, but for young plants, root extension, up to several miles per day per plant, is required to maintain a continuous supply of water. As shall be seen, this has relevance to mechanical impedance.

Soil Aeration

Brown et al. (13) suggest that oxygen is the most important single constituent of the air in the soil (soil air) with regard to root growth and plant enlargement. They found that the consumption of oxygen was directly related to the size of the plant and the amount of organic matter in the soil. Gill and Miller (36) found that reducing the oxygen content of soil air to about 10 percent adversely affected plant growth. They report an interaction between mechanical impedance and aeration. Growth did not cease with very low oxygen content in the absence of mechanical impedance, but with impedance, a small reduction in oxygen supply impaired root enlargement.

Wesseling and van Wijk (96) comment that oxygen consumption varies with the type of plant and that it increases with temperature. They declare that the oxygen content of soil air decreases with depth with an increase in the level of carbon dioxide; this being largely a function of the respirational behaviour of roots on the one hand and rate of diffusion from the atmosphere on the other. Russell (73) noticed that in a poorly oxidized soil, toxic compounds such as methane and ammonia may be found. These products in a well-oxidized soil are transformed to simpler forms such as carbon dioxide and nitrogen by aerobic organisms. Wesseling and van Wijk (96) conclude that the large or macro pores, which drain easily, are of great importance to aeration. According to Hill and Sumner (48), it is these large pores that are affected most readily by moderate compaction. Only with severe compacting pressures are the small or micro pores reduced. Wesseling and van Wijk (96) assert that for adequate aeration, the water table would have to be more than two feet below the soil surface. This has relevance to the perched water tables and traffic soles noted previously.

Soil Temperature

Hagan (41) has written that soil temperature exerts "... a greater influence on early season growth of some young plants than on the summer growth of more mature plants of the same species." In general he asserts that temperature and cell division are directly related. In addition, he declares that temperature is a most important factor with respect to germination and emergence. With regard to the former, he wrote, "Alternating rather than constant temperatures appear to be more favourable to the germination of many seeds and are apparently necessary for germination of the seeds of some plants."

Richards (70) comments that soil temperature is largely a function of the solar radiation. The effect of the latter is modified somewhat by other meteorological phenomena and by such factors as evaporation at the soil surface and the thermal properties of the soil. With regard to the minor role of tillage, Lyon and Buckman (61) have written, "The temperature of field soils is subject to no radical human regulation, yet soil-management methods, especially those that influence soil moisture, provide for small but biologically vital modifications." Richards (70) provides a specific example, "... well-drained soils show faster temperature changes in response to external factors than the same soils with higher moisture." A well-drained soil, in other words, would warm quickly in the spring, resulting in early germination and emergence. On the other hand, mulch, either artificial (organic) or natural (loose, dry soil), reduces the soil conductivity so that less heat is transferred to the lower layers (61). Either type of mulch is governed to a degree by the tillage practices used.

Mechanical Impedance

Rapid root extension is essential for the supply of water to a developing plant, particularly in the sub-humid climates. Extension can be limited by the mechanical impedance of the soil as suggested by Eavis (25). Experimenting with peas, he determined that the length, volume, and fresh weight of roots was a function of this impedance or soil density. Aubertin and Kardos (5) found that maize roots did not grow in a porous but rigid system when the pore diameters were less than 138 mm. They found some reduction in root growth when the pore diameters were less than 412 mm. They conclude, however, that plant roots generally do not grow through existing pore space but by their ability to displace the soil particles and create their own path through the soil. In this connection, Barley (8) wrote, "Soils resist the local deformation caused by roots, and, as there is definite upper limit to the pressure which can be exerted by roots of a given species, growth may be prevented if the strength of the soil is sufficiently large." He found, for example, that root elongation of corn was prevented when the shear strength of the soil was greater than 0.3 kg/cm^2. Abdalla et al. (1) observed that roots grow with difficulty if the deformation stresses of the soil are in the region of 3 to 10 lb/in^2 (0.2 to 0.7 kg/cm^2). For larger values, growth was severely arrested.

Taylor and Burnett (88) stated the effects of soil strength very explicitly; "The results show that it is soil strength, and no other physical factor of the soil, that controls growth of roots through this moist soil." Soane (81) takes issue with this statement on the basis that aeration ".... may be severely deficient in certain compacted soils." Abdalla et al.(1) suggest an interesting "mechanics" with regard to root extension. They conclude that roots penetrate soils offering impedance to axial growth by radial thicking which reduces the soil resistance to axial elongation. They declare that radial straining induces smaller elastic stresses than axial, for the same magnitude of strain.

With regard to traffic soles, their existence in cultivated land appears to be better known, though not necessarily better understood, as larger tractors and tillage units are used. Free (33) reported in 1952 a traffic sole or compacted layer of soil below plough depth when intensive cropping had been followed for several years. He found no such layer in adjacent range or wooded land. What is not clear, however, is whether the mechanical impedance of such soles reaches detrimental levels in the overall case. Soane (81) quotes the results of a number of authors proving that, in certain situations, detrimental levels have been reached. On the other hand, it is a popular belief in some parts of the temperate zone that frost prevents the development of a traffic sole.

Summary

The soil pulverization process of tillage as defined is useful in the control of weeds and can provide temporary, but effective, control of soil erosion by wind and water. The process has a minor role with respect to the primary edaphic factors which, to an extent, govern plant growth. Of these, the reduction of the mechanical impedance by reducing the soil strength with loosening of the soil, appears to be the most important. It is interesting to speculate that the decrease in soil strength may be the primary aim of "seed-bed preparation", an often-stated function of tillage.

The situation with regard to traffic soles is somewhat confused. It seems reasonable, however, to expect detrimental levels of mechanical impedance to impose a limit on the maximum size of the tractor and tillage unit. A method to transmit energy from the tractor to the tillage tool, without increasing the vertical load at the soil/wheel interface, has merit. One of these appears to be forced vibration of the tool.

CHAPTER 3

SOIL MECHANICS

Introduction

Soil mechanics is a branch of knowledge concerned with the properties of soils and their behaviour. Such a broad definition could include tillage. In practice, however, its meaning has been restricted somewhat by the interest of the civil engineer in bearing capacity and stability, which are quasi-static in nature. Even though tillage is dynamic rather than static, some aspects of soil mechanics are pertinent to tillage.

The difficulties in devising a model, or a "mechanics", which will account for the behaviour of soil is formidable. In the first place, soil in situ is a semi-infinite medium bounded by the ground surface. Soil itself is a complex material. Gupta and Pandya (40) have written, "... soil is a deformable body whose behaviour falls between a linear elastic solid and ideal viscous liquid.... ." In other words, it exhibits elastic, plastic, and viscous properties in various combinations. Its strength varies widely. Lambe (57) states that the shear strength of fine grain soils is a function of the electrical forces between the particles which in turn are a function of particle spacing, orientation, externally applied forces and characteristics of the soil/water system.

Stress/Strain Relations

A widely used model in the applied sciences has been the linear stress/strain relation which is sometimes referred to as the theory of linear elasticity. Gill and Vanden Berg (37) point out that neither this theory nor the plastic theory, where the strain is time dependent, are adequate for soil. An example of the former is the attempt of Vanden Berg et al. (91) to relate soil compaction and stress. Using continuum mechanics they hypothesized that volume strain is directly related to the mean normal stress, σ_m, where,

$$\sigma_m = 1/3 (\sigma_x + \sigma_y + \sigma_z),$$

and where σ_x, σ_y, and σ_z, are the normal or the perpendicular stresses on the face of an infinitesimally small soil cube. Such a relationship is vital to a soil compaction theory. Unfortunately, Harris et al. (42) were unable to accept or reject the hypothesis in a experiment especially set up to test it.

Schofield and Wroth (74), using a critical state or critical void ratio concept, propose that some soils, when stressed, consolidate and then dilate. Observations by Olson and Weber (65), with model tillage tools, suggest that such a concept should be germane to a tillage theory. The application of the concept will be difficult. Schofield and Wroth (74) limited their models to a dry sand and a saturated clay, neither of which is typical of an agricultural soil.

Gill and Vanden Berg (37) advocate that need for suitable stress-strain relationships for soils. They have declared, "Until such relationships are determined, one cannot study the dynamic properties of soil because they have not been clearly identified." Of special interest is Olson and Weber's (65) suggestion that a relationship exists between the shape of the stress/strain curve for soil, and the magnitude of the increase in tillage tool force with an increase in speed. It is fitting to note Schofield and Wroth (74). They have written, "Often, as engineers, we speak loosely of the relationship between stress increment and strain increment as a 'stress/strain' relationship, and when we come to study the behaviour of an inelastic material we may be handicapped by this imprecision." Soil is an initially stressed body to which a stress increment is applied, producing a strain increment.

Soil Failure Behaviour

Two behaviour properties or parameters of the soil have been identified when the soil is at the point of failure. They are the apparent cohesion and the angle of shearing resistance, which are defined in the following equation. Failure is defined as the state of stress that causes fracture or incipient plastic flow. The relationship (74) of these parameters is:

$$\tau = c + \sigma \tan \phi$$

where τ is the shearing stress (maximum),

σ is the normal stress,

c is the apparent cohesion,

ϕ is the angle of shearing resistance.

Although this relationship is attributed to Coulomb, others have made important contributions. Mohr has provided a graphical representation (see Figure 2) in which the critical values of the shearing stress and the normal stress may be rendered as a straight line. The apparent cohesion is the intercept of this line with the shear axis and the angle of shearing resistance is the slope.

The relationship of the principal stresses (major and minor) with the shear and normal stresses, and their respective planes, can also be represented graphically. It is known as Mohr's circle of stresses. The difference between the plane of the major principal stress, σ_1, and the plane containing the critical shear stress, τ, is θ where θ is equal to $45^\circ - \phi/2$. This may also be seen in Figure 2.

MacLean et al. (62) advise that the apparent cohesion and the angle of shearing resistance of Coulomb's equation are not fundamental properties of the soil. Other authors usually agree. Gill and Vanden Berg (37), for example,

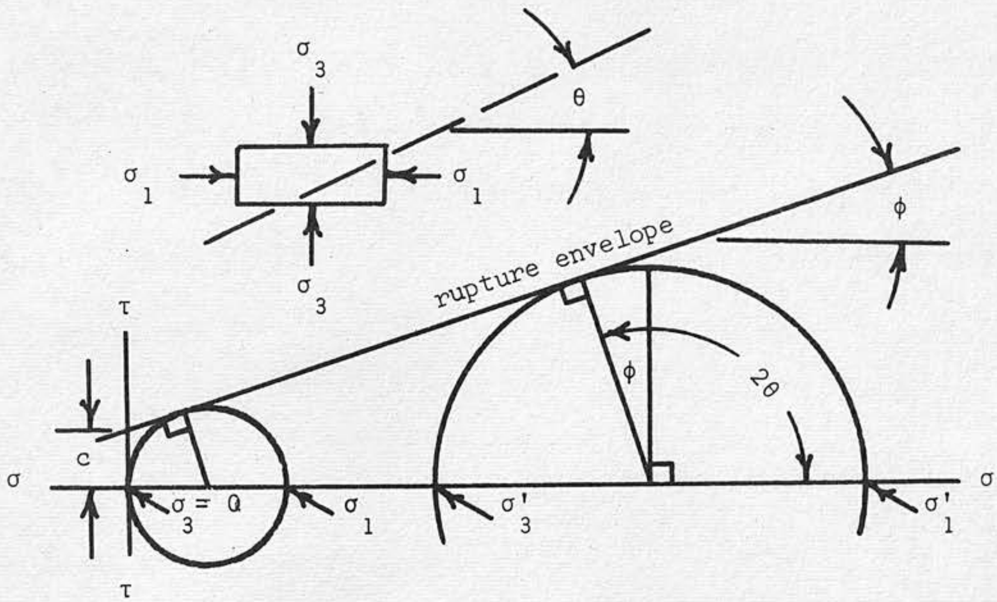


Figure 2 Mohr's Stress Circles and Rupture Envelope.

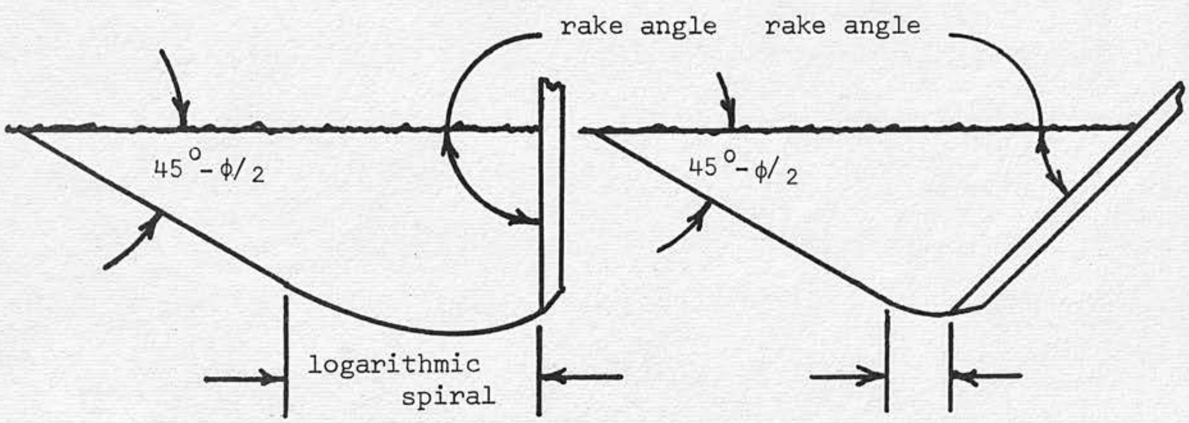


Figure 3 The Change in the Failure Surface with a Change in the Rake Angle.

assert that they are parameters only of the assumed failure equation. According to MacLean et al. (62), the fundamental parameters of shear strength are approximated when the pore/water pressure is subtracted from the normal stress. They have added, "Not all authorities on soil mechanics would accept this definition of the true cohesion and true angle of internal friction." Gill and Vanden Berg (37) record a further caution with respect to Coulomb's equation. It represents shear failure at a single point and "is clearly represented by a plane." The distribution of the shear point failures in the soil, on the other hand, "is a surface that can have any shape".

Failure Surface

According to Osman (66), Ohde is credited with determining the shape of the failure surface (distribution of the shear point failures) for applications in foundation engineering, though others, such as Terzaghi and Peck (90), appear to have made important contributions. Of interest to tillage is Terzaghi's and Peck's (90) solution of a retaining wall which causes upheaval of the soil. According to Gill and Vanden Berg (37), the orientation of the principal stresses does not remain horizontal and vertical, but rotates as one proceeds downwards along the failure surface. The soil/wall or the soil/tool friction is the cause of this rotation. The solution which satisfies this criterion is a logarithmic spiral with a plane portion near the ground surface at an angle of $45^{\circ} - \phi/2$ to the horizontal. This may be seen in Figure 3. According to Terzaghi and Peck (90), "the error is tolerable" using Coulomb's theory (plane failure surface) if the soil/wall friction is small. The advantage is a simpler solution than that required for a curved failure surface.

With respect to the Mohr-Coulomb theory, Yong and Osler (98) have stated ".... success has been achieved in the solution of essentially static problems involving bearing capacity and stability.... ." Part of the success, they claim, is achieved by avoiding the yield point of the soil with the use of suitable "safety factors." The authors note two difficulties with respect to applying conventional theories of soil behaviour to problems in tillage. They are:

- the three-dimensionality of the problem, and
- the rate effects of "soil dynamics" and, in particular, the generated pore pressures, their distribution and possible dissipation.

Soil Index Properties

The soil index properties (individual grain and aggregate) are of importance to agriculture. They are of importance in the behaviour of soil too because the size and shape of the individual grains affect the soil strength. For example, sand containing smooth and rounded grains or particles has a smaller angle of shearing resistance and, therefore, is weaker in shear than a sand made up of particles that are rough and angular. Aggregate properties such as structure (qualitative) and density (quantitative) affect the soil strength to an even greater degree. The major aggregate properties which affect soil strength, according to Terzaghi and Peck (90), are:

qualitative	quantitative
- texture	- density
- structure	- moisture content
- consistency	- porosity (air filled)

It is necessary to recognize that in "soil mechanics", soil strength and soil shear strength are often synonymous. Soil for construction purposes is considered to have no tensile strength and, therefore, is only loaded in compression, with failure, if it occurs, by shearing. Gill and Vanden Berg (37) point out that the tensile strength of soil, though never large, can at times be significant.

Relationships, empirical or otherwise, between soil strength and the index properties appear to have met with little or no success. This is due in part to the interaction of the aggregate properties. An example is the empirical relationship of Nichols' (64) between the shear strength and the moisture and clay contents. Harrison and Cessford (43) note that Nichols appears to have determined shear/strength values in such a way that the maximum always occurred at the lower plastic limit, an Atterberg plasticity characteristic. Vomocil and Chancellor (93) conclude that the role of water in soil strength may change with water content in a manner not adequately described by the Atterberg limits. The latter authors found the existence of maximum and minimum peaks in the strength/moisture content relationship and which were not related to the lower plastic limit. They propose that a change in the failure mechanism occurs with the change in soil consistency from "plastic to brittle" as the soil dries. As they have expressed it, "The cause of this behaviour is not understood and on the basis of available data, must remain the subject of speculation."

With respect to the other aggregate properties, MacLean et al. (62) remark that the strength increases with increasing dry density. They caution that dry density and moisture content are to a "certain extent inter-related." The same authors point out that remoulded or structureless soil may be considerably weaker than an undisturbed soil. They also state, as do other authorities, that soil strength is also a function of the testing method. One variable of a soil-testing apparatus is the rate of loading. Very low rates of loading are of interest when designing foundations but, as concluded by Olsen and Weber (65), "Conventional soil shear strength measurements are not adequate for prediction of tool forces under dynamic conditions."

Dynamic Soil Strength

According to Casagrande and Shannon (18), soil strength (shear) of an undisturbed soft organic clay increased 40% when the loading time was reduced from 150 to 0.01 seconds. Rowe and Barnes (72), using a maximum loading velocity of $1\frac{1}{2}$ miles per hour, obtained a 25 to 30% increase in strength when the loading rate was increased 35 times. The range of strength increase covered a full range of soils from sands to clay. Telischi et al. (89) found an important interaction of draught, speed and soil. Draught was a function of speed unless the moisture and clay contents were low.

In the face of this evidence, it is significant to record the work of Hendrick and Vanden Berg (45) with dynamic tensile failure. They found that the loading rate had no effect on the ultimate tensile strength of clay. Of particular interest is their observation that less energy is required to cause failure when the tensile loading rate is increased.

Energy Disposition in Soil

For soil failure due to compressive loading, Bateman et al. (9) found that the energy requirement was related to the resulting size of the clod. They note an important interaction. When clods are small, the energy input is a function of the loading rate and the initial bulk density. Vomocil and Chancellor (94) found that the energy requirement;

- is greater for compressive loading than tensile,

- is several times greater for compressive loading when the soil is subjected to a confining stress, and
- varies with moisture content.

They propose that there is a non-productive release of energy which is absorbed by the soil not adjacent to the fracture surface. With regard to the variation with moisture, Fox et al.(32) found for a clay loam "that a minimum shearing energy occurred at two different moisture contents; namely 17 and 24 percent .... ." Chancellor et al.(19) determined that 15 to 25% of the total energy input is used to compact the soil for unconfined compression while the remainder is largely associated with the shear/strain process. For compressive loading, Bailey and Vanden Berg (6) observed, ".... yielding of initially loose, unsaturated soil will occur in two distinct manners; first by compaction and then by shear. A compacted soil mass may yield in shear directly." This agrees with the concept of failure as suggested by Schofield and Wroth (74).

Hendrick and Vanden Berg (45) attribute the smaller energy required to cause tensile failure to the fact that rapidly-loaded samples strained less before failure. Vomocil and Chancellor (94) appear to suggest the same. This failure may also be caused by the soil behaving as a rigid body. Gill and Vanden Berg (37) have stated, "When soil does not act as a rigid body, the behaviour induces shearing stresses."

The implications of the above may be more readily seen when it is appreciated that soil pulverization with conventional tillage equipment appears to occur as suggested above by Bailey and Vanden Berg. Vomocil and Chancellor (93) term this description of stresses as a "frictional" model. In this situation, an upper limit to tillage speed is imposed by the appreciable cost of the extra energy. On the other hand, if soil failure is obtained by the breaking of the soil bonds in tension ("cohesal" model), there may be no upper limit. In addition, as already noted, soil is considerably weaker in tension than compression. If vibratory tools are able to substitute, or partially substitute, the "cohesal" model for the "frictional model", then tillage efficiency could be increased.

The distinction between soil mechanics and soil vibration mechanics is not readily apparent in the literature. On the other hand, it seems useful to make such a distinction because of the desirable emphasis and the objectives of the experimental work. The arbitrary distinction made here is on the basis of the type of loading. Repetitive impulse loading is considered under soil vibration mechanics. Single impulse loading has already been considered under soil mechanics.

Dimensional Analysis and Similitude

Murphy (63) expounds the advantage of using dimensional analysis for studying the behaviour of a system. Kondner (54) finds it particularly useful in soil mechanics. According to him, dimensional analysis and the theory of similitude provide a rational basis for transformation from model studies to prototype response. Murphy (63) and Sprinkle *et al.* (85) note three additional advantages which are:

- reduction in the number of variables to be investigated,
- systematic collection of data, and
- assistance in formulating a single general equation.

The work of Freitag (34) and Kondner (54) may be cited as examples of these advantages, particularly with regard to the last. In an off-road application, Freitag (34) found a relationship between such performance parameters of a pneumatic tyre, as its pull divided by the load, and a dimensionless ratio he calls the mobility number. The latter contains a measure of the soil strength as well as a number of conventional tire specifications. Kondner (54) determined that the relationship between the penetration parameter, x/c, for a 60° cone and the strength ratio, $F/A\tau$, was linear except for small values where;

x is the penetration,

c is the perimeter of the cone,

F is the total applied force,

A is the cross sectional area of the cone,

τ is the maximum unconfined compressive strength of the soil.

It should be noted that the simple relationship was achieved by limiting it to a 60° cone and using a low penetration rate. On the basis of the latter, it was possible to omit a creep parameter. For soil vibration mechanics, dimensional analysis loses some of its simplicity. This will be noted in subsequent chapters.

Summary

The complexity of soil is a serious obstacle in the development of suitable stress/strain relationships. As a consequence, it has been impossible to formulate a rigorous and inclusive mechanics for tillage. The complexity also hinders the assessment of the energy requirements of cultivation. Dimensionless analysis appears to be a useful alternative to a rigorous mechanics. As noted later in Chapter 5, the behaviour of soil at point of yielding is a most useful concept for the draught of tillage tools. The soil index properties in a tillage experiment require attention because of their relationship to the soil strength. The dynamic soil strength has broad implications. High speed cultivation using small tractors is penalized.

CHAPTER 4

SOIL VIBRATION MECHANICS

Introduction

Soil vibration mechanics may be defined as the application of a rapidly varying force to the soil through a soil/machine or soil/tool interface. As so defined it would include compaction as well as tillage. It is a relatively new field and, therefore, this definition is offered with some apprehension. Skelton and Tobias (80) report on investigations of vibratory cutting of metals. The authors note many advantages of a vibratory tool and conclude the most significant for metal cutting is chip breaking. Of interest here is the large reduction in cutting forces obtained; up to 75%. An interesting comment by these authors is, "There appears to be considerable doubt as to the exact mechanism which causes the reduction in cutting force when vibrating the tool in the direction of feed."

Cowin et al.(22) comment that there are relatively few references bearing directly on vibratory cutting and penetration of soil. Russian scientists appear to have investigated the mechanics more extensively than others. Even Skelton and Tobias (80) refer to Russian publications with respect to metal cutting. Barkan (7) appears as an authority on the subject with respect to soil, and refers to experimental work of his own conducted in Russia as early as 1934. Russian engineers have developed very large vibrators, ranging up to five tons in weight, for driving sheet pile. They utilized them to drive piles at the Gorky Hydroelectric Development in 1949 (7).

Cohesionless Soil

Barkan (7) distinguishes between the force required to overcome friction due to adhesion of the soil on sheet piles or poles, and that required to deform or displace the soil. He refers to the former as "skin friction" and the latter as "point resistance." He found that skin friction could be reduced by as much as 96% by using a vibrator. His experiments also indicated a reduction in the "internal friction" of sandy soil. It appears that he is referring to the parameter ϕ of Coulomb's equation. He concludes the following additional points from his own work and that of his colleagues;

- there is a minimum or critical amplitude of vibration,
- pile-driving speed is directly related to the amplitude when greater than the critical value,
- the size of the zone of vibrating soil surrounding the pile is related to the "acceleration of the oscillations,"
- point resistance increases with frequency, and
- point resistance increases exponentially with the cross-sectional area of the pile.

The basis for his second conclusion was from observations in driving 325 mm diameter pipe. Doubling the amplitude from 8 to 16 mm increased the driving velocity from 1.2 to 6 m/min, an increase of 500%. He makes no reference to the energy input in these experiments. As to the "acceleration of the oscillations", this appears to be some function of the amplitude and frequency.

Kondner and Ayre (55) confirm Barkan's observation of an increase in point resistance with frequency. There obviously must be an optimum frequency for maximum penetration velocity because the static state is approached as the frequency approaches zero. Kondner and Ayre (55) obtained a maximum penetration which was associated with a natural frequency of the "soil-vibrator-system." This is within the region of 6 to 40 Hertz (cycles per second) which, according to Barkan, is the frequency range of four models of the vibrators used in Russia. It should be recognized that the optimum frequency referred to is with respect to pile driving speed or maximum penetration and not to the efficiency of energy used. With regard to Barkan's last conclusion, he states that this limits the practical application of the vibration method of driving piles. It is not expected that this would be a factor in vibratory tillage with the possible exception of large subsoilers.

Gumenskii and Komorov (38) propose that sandy soils may be characterized by a "coefficient of vibroviscosity" since soil, when shaken, acquires the properties of a viscous liquid. They advise that the "coefficient of internal friction" of sand is inversely related to the frequency. It appears that they too are referring to the parameter ϕ of Coulomb's equation.

Cohesive Soil

The successful achievement of the Russians in driving sheet piles and pipes with vibrators has been largely confined to sands and gravels which are low in cohesion. Kondner and Edwards (56) in the U.S. experimented with cohesive soils. They wrote, ".....soil properties are definitely frequency-dependent and their strengths can be greatly reduced by vibration," and in a more specific reference, ".....penetration of cohesive soils is a rate process in which the vibratory energy is a form of activation energy....". Another interesting comment is, ".....activation energy involved in the changing of the internal structure of a soil could possibly be mechanical, electrical, thermal or magnetic in its nature." With regard to penetration they found that it increased with the amplitude of oscillation and the force ratio. The former is similar to Barkan's observation for sand. The latter refers to the downward force applied to a pile or pole which varies in magnitude from a minimum to a maximum during one oscillation.

Kondner (53) draws attention to the fact that the change in soil strength due to vibration is contrary to the response when soil is subjected to a single-acting, rapidly-applied load. He found with vibratory loading that the soil strength "was only one-half to one-fifth of that obtained by the conventional unconfined compression test, depending on the moisture content of the specimen." He declares that the ultimate soil strength was virtually the same as the yield strength for vibratory loading.

With respect to clay soils, Gumenskii and Komarov (38) discuss the phenomenon of thixotropy which they define "as the capacity for isothermal reversible change from a gel to a sol during mechanical disturbance to the bonds in the framework of the soil." They partially attribute thixotropy to water that has been freed (liquefaction) from a physical-bound or immobilized state during vibration. In specific drilling experiments they "gained the impression that the drilling was being done in soil completely saturated with water, but no free water was encountered in the hole." The authors record some disagreement on this explanation of thixotropy during vibration. One interesting condition for thixotropy is that at least 2% of the particles must be smaller than .002 mm. They also observe that the dimension of the zone within which liquefaction occurs is only several millimeters thick. This is comparable to Barkan's (7) observations with sands. The authors did not report the frequency and the amplitude of vibration. The omission is not important here as it appears that the rate of penetration they used is low relative to typical tillage speeds.

The value of changes in soil strength caused by thixotropy and fluidization (vibroviscosity) to vibratory tillage is not clear. Senator and Warren (76) deliberately omitted such phenomena in their investigations of a vibratory plough. They reason that the soil model should apply to a wide variety of soils whereas thixotropy and fluidization are limited to certain types. In their modified Coulomb soil model, for example, they simply defined the resistance of the penetrated soil as a small fraction of that of the unpenetrated soil. On the other hand, Kondner (54) decided to use dimensional analysis in his investigations of vibratory soil mechanics because he was unable to specify the penetrated and unpenetrated soil resistance, apparently thinking that the range of the difference was large.

Senator (75) makes a useful observation with respect to the Coulomb soil model. He considers any backward motion of the penetrator tip as wasted energy, serving no useful purpose. He suggests that, in driving piles, backward motion may be reduced by increasing the static weight of the pile or vibrator. To do so in the case of tillage tools, it would be necessary to increase the draught by such expedients as increasing the ground speed. Irrespective of the mechanism to increase the draught, Senator's comments suggest that minimum total energy for tillage will not be coincidental with minimum draught energy.

Dimensionless Model

Kondner (54) applied the techniques of dimensional analysis to the behaviour of a vibratory tool penetrating soil. He selected fourteen physical factors or variables using three fundamental units to describe the phenomenon. By restricting the problem, he reduced the normally-required eleven independent dimensionless ratios to six. The resulting relationship is as follows:

$$x/c = f(F_t/A\tau, F_t/F_s, \omega\eta/\tau, c^2/A, \theta)$$

where x is the penetration of the tool,

c is the perimeter of the tool,

F_t is the total applied force,

F_s is the static force,

A is the cross-sectional area of the tool,

τ is the maximum unconfined compressive strength of the soil,

ω is the frequency of vibration,

η is the viscosity of the soil,

θ is the angle of tool with respect to direction of penetration.

Even with this simplified relationship, Kondner (54) found "the amount of work required to graphically determine the explicit form of the equation extremely great." The form of the equation is suitable for penetrators, such as piles, driven to specific distances or depths. For tillage, the rate of penetration or velocity is of prime interest and, therefore, a time quantity is needed. In addition, the relationship ignores the amplitude. As will be noted in the next chapter, draught and torque inputs to a vibratory tool appear to be dependent on these two variables as well.

Summary

It is apparent that the vibration of a soil-cutting tool will reduce the "point resistance" in either a cohesive or cohesionless soil. The resistance is evidentally a function of the frequency and amplitude. The relationship has not been quantified for either type of soil. In spite of this imprecision, some useful observations can be made. In particular, there appears to be an optimum frequency with respect to the cutting resistance. It also appears that there is a minimum amplitude of oscillation. Of interest is the possibility that the minimum draught and the minimum energy requirement for penetration may not be coincidental. Also of interest is that many of the required dimensionless parameters for vibratory tillage analysis are defined by Kondner (54).

CHAPTER 5

SOIL/TOOL MECHANICS

Introduction

As no suitable theory for the behaviour of soil in the dynamic situation has been formulated (37), soil cultivation must be considered an art. It may be due to its antiquity that only recently has it received attention and some important contributions been made. Hettiaratchi (46) provides a starting place for a soil/tool mechanics and relates it to the agronomic requirement. He states that pore space is increased with the application of a large shear stress and a small normal stress, and notes the opposite magnitude of stresses for consolidation or pore space reduction. Bailey and Vanden Berg (6) express the former in mathematical form where:

$$\text{BWV (bulk weight volume)} = f(\sigma_m, \tau_{max.}).$$

Rigid Tool Tillage

Payne (67) applied Terzaghi's techniques for solving passive earth pressure on a retaining wall with a curved failure surface, to vertical tillage tines, with reasonable success. For example, he was able to confirm that the curved failure surface "is almost exactly as predicted." More recently, Siemens et al. (79) noticed that, for tools with a rake angle less than 70°, the failure surface is a plane inclined at $45^{\circ} - \phi/2$. They reason that the leading edge of tools with small rake angles cancel out much or all of the logarithmic spiral. This may be seen in Figure 3. Olson and Weber (65) found there was no significant change in the angle of inclination of the failure plane with a change in speed. Osman (66), however, concludes that the simple plane failure surface of Coulomb's theory is "grossly inaccurate except for smooth blades in dry sand."

About the same time as Payne, Söehne (84) applied Coulomb's equation to an inclined tillage blade. He determined the relationship of draught and the soil parameters c and ϕ based on a plane/failure surface inclined at an angle of $45^{\circ} - \phi/2$ to the horizontal. Discrepancies occurred between the predicted and measured values. According to Gill and Vanden Berg (37) "the values are close enough to indicate that the mechanics is not completely wrong." Several possibilities exist for improvement. One of these (Osman) has been noted. Another is that the failure plane is influenced by the rake angle of the tool. This interaction was revealed by N. Kawamura according to Gill and Vanden Berg (37) and later confirmed by Osman (66). Another is that Söehne neglected the force to cut the soil. Hendrick and Buchele (44) in their experiments found that cutting the soil with a wire was nearly 50% of the draught of a simple tool. With regard to cutting,some researchers treat it as a phenomenon distinct from rupture while others make no such separation. The difference between the two appears to be a matter of degree rather than of kind. Cutters of practical dimensions result in deformation of the soil, though they will infrequently cause sufficient strain to rupture the soil. Gill (35) observes that the force required to cause penetration of a wedge or cutter is closely related to the volume of soil displaced regardless of its shape.

The application of Coulomb's theory of soil behaviour to tillage is limited, as Elijah and Weber (29) note. They identified four distinct failure patterns which they designated as shear-plane, flow, bending, and tensile. Only the first two are accounted for by the mechanics of Payne and Söehne. Even here the theory will not describe the observation of Sprinkle et al.(85); namely a transition of shear-plane to flow-failure with a decrease in speed.

This also is the conclusion of Olson and Weber (65). Elijah and Weber declare, "To predict when these patterns will occur and what tool forces are involved, some new soil parameters will be needed." One of these new parameters, for example, appears to be viscosity, as identified by Kondner (53).

The lack of a rigorous mechanics for the rigid tool is a sufficient discouragement at the moment to preclude any thought of developing one for a vibratory tool. The present limited mechanics might be extended into vibration tillage. There is also the possibility of developing relationships between the draught, torque, mechanical variables of vibration, and some suitable soil variables with the aid of dimensional analysis. The general equation of the required relationship would include the dimensionless ratios identified previously by Kondner (54), but in the form used by Luth and Wismer (59). Their dependent ratio for example, was $F/\gamma L^3$ where;

F is the draught,

γ is the soil density,

L is a dimension of the tool.

One of their independent ratios contained the tool velocity, but, as they were using a rigid tool, frequency and amplitude were not included. With this in mind, it is useful to note the development of a dimensionless ratio of vibration.

Vibratory Tillage and Draught

Most research workers dealing with vibratory tillage tools have chosen some parameter in an attempt to describe the oscillation. Dubrovoski (23) introduces ".... the concept wavelength of oscillation...." where;

wavelength = forward speed/frequency of oscillation.

His experimental results revealed that the draught of a vibratory tool decreased as the wavelength decreased. In addition, he wrote "....a working element which is not subjected to oscillation....", is also a vibratory process. Blight (10) in his summary may have stated it more succinctly, "...it was concluded that the action of a nominally rigid tine was actually a special case of vibratory movement."

About the same time as Dubrovoskii's work in the U.S.S.R., Gunn and Tramontini (39) in the U.S. defined a dimensionless quantity, K, where;

$$K = \text{forward velocity}/\omega r$$

where ω is the angular velocity,

r is the eccentricity of the crank.

Blight (10) notices the similarity between K and Dubrovoskii's wavelength and, in particular, the relationship between the two, where;

$$\text{wavelength} = K(r/2\pi)$$

Gunn and Tramontini (39) report a relationship between the magnitude of K and the draught similar to that between Dubrovoskii's wavelength and the draught. In their case, the draught approaches a maximum when K is 3. Gunn and Tramontini's work suggests the following:

- as K approaches zero so does the draught, and
- the total power requirements are unchanged.

Eggenmüller (27) in Germany, who was also working about the same time as Dubrovoskii, Gunn and Tramontini, added another variable to vibratory tillage technology. His experimental apparatus was so constructed that the plane of oscillation was not in the same plane as the travel of the implement and tractor. In order to accommodate this new variable, he defined a dimensionless ratio z, where;

$$z = \text{forward velocity}/2Af \sin \phi$$

where A is the amplitude (zero to peak),

f is the frequency,

ϕ is the angle between the plane of oscillation and the plane of travel.

Unfortunately, the addition of the trigonometric function, $\sin \phi$, causes some difficulty when ϕ approaches zero. In another publication, Eggenmüller (28) defines another dimensionless parameter z', where;

$$z' = \text{forward velocity}/Af$$

The main distinction between z and z' is the trigonometric function, $\sin \phi$. The ratios K and z' are very similar and, with r equal to A, the relationship between them is;

$$K = z'/2\pi.$$

More recently Kofoed (52), in his review of published experimental work on vibratory tillage, defined another dimensionless ratio, λ, where;

$$\lambda = \ell/2r$$

where ℓ is the distance travelled in one oscillation,

r is the radius of oscillating crank (or eccentricity).

Kofoed (52) suggests that the critical values of λ would occur in the region between 0.68 and π. The basis for this suggestion appears to be that backward movement of the tool relative to the soil would occur, but would not be excessive. Again there is similarity between this dimensionless term and some of those noted previously. If r is again equal to A, then;

$$K = z'/2\pi = \lambda/\pi$$

Dubrovoskii's wavelength and Eggenmüller's z have been omitted in the above. The former has the disadvantage of being a dimension and the latter experiences difficulty with the trigonometric function.

Blight (10), in his summary, notes the draught reduction and value of z' from the work of a number of researchers. A plot of this information is given in Figure 4. The poor correlation may be attributed to variations such as the soil conditions, tool geometry, mode and plane of oscillation used by the various researchers. On the other hand, soil conditions alone may be the sole cause. For example, Wismer et al. (97) obtained a similar scatter diagram to the above for a subsoiler under field conditions whereas Eggenmüller obtained a good correlation using a remoulded soil. The latter may be seen in Figure 5 top which implies the following relationship;

$$\text{draught reduction} = f(z').$$

The amount of scatter in Eggenmüller's data (27) may be random, in which case the draught reduction is directly related to z'. On the other hand, the scatter may be caused by the interaction of the independent variables. In spite of this uncertainty it is an advantage to use z' or one of the other dimensionless parameters whenever possible. For example, Johnson and Buchele (50) obtained only a 10% reduction in draught using a vibratory tool. They attributed the small reduction to the higher clay content of their soil compared with that used by other investigators. The small reduction might also be accounted for by the large z' which was equal to 13.5.

Vibratory Tillage and Energy

Gunn and Tramontini (39), and later Hendrick and Buchele (44), remark that the total energy required by a vibratory tool was not much different from that of a rigid tool even when they obtained a large reduction in draught. Wismer et al. (97) have written, "....large draught reductions obtainable by vibratory soil cutting may come at the expense of higher total power requirements." This suggests that part of the required energy is simply transmitted to the soil by a different mechanism which, as they have pointed out, is still of economic

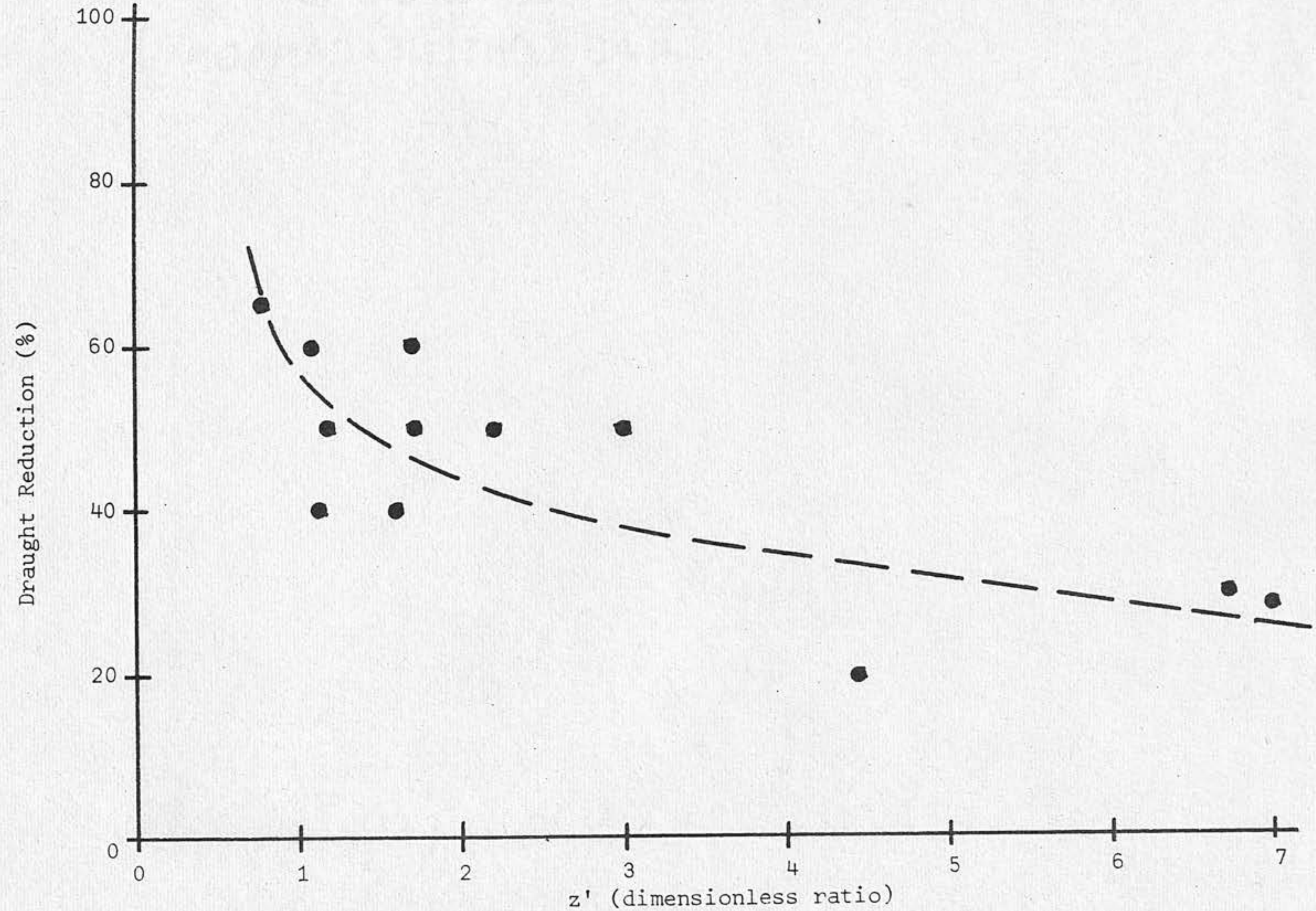


Figure 4 Summary of Vibratory Tillage Results (10).

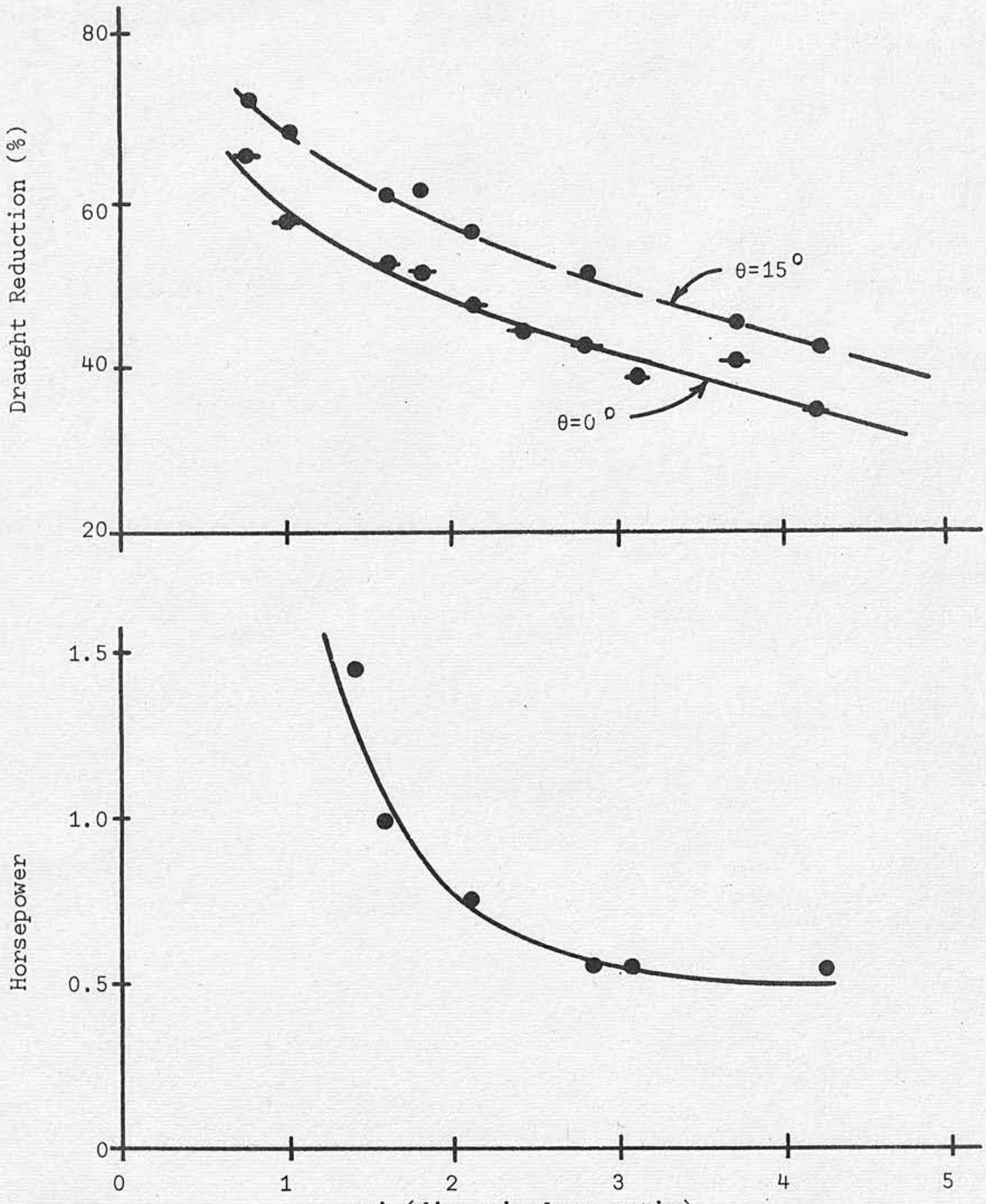


Figure 5 The Draught Reduction (top) and Power Requirements (btm) - Eggenmüller (27).

value. Transmitting energy by virtue of the tractor wheels is less efficient than directly powering the vibratory tool through the tractor's power take-off. If this observation is valid for all cases, it has not been sufficient inducement to date for either the farm-implement manufacturer or his farmer-customer to take advantage of this technology. No doubt they have hesitated because of the much greater complexity of a vibratory tool. Eggenmüller's results are even less of an inducement. A plot of the horsepower input to the oscillating drive versus the dimensionless ratio z' that Eggenmüller (27) reported may be seen in Figure 5 btm. Unfortunately he has not recorded the total power requirements, or the actual draught so that the total cannot be calculated either. From the slopes in Figure 5, however, the total power requirement must have increased rapidly for z' less than 2. In another paper on oscillating a plough body, he (26) reports the total power requirement to be 30 to 100% greater than for a rigid body. On the other hand, Dubrovoskii (24) reports a 35% reduction of total power for vibrating a "ditcher." Eggenmüller's increase in power seems somewhat surprising in view of his suggested mechanics of soil disruption with a vibratory tool, namely that the shear area of the failure plane is smaller than for a rigid tool. Venter (92) seems to have used the same concept to develop his "vibratory plough". He obtained a 39 to 45% energy reduction for soils ranging from sand to heavy clay, all at field capacity. He claims that he owes his success largely to seeking minimum energy rather than minimum draught. Venter's reasoning in this regard may be valid. For vibratory tillage to be a commercial success, it appears that the energy efficiency must be greater than for conventional implements.

Vibratory Tillage and Soil Tilth

Soil tilth is defined (21) as "the physical condition of the soil as related to its ease of tillage, fitness as a seed bed, and its impedance to seedling and root penetration." From this definition, it is an important characteristic of agricultural soils, but is qualitative, not quantitative. As a result, it is necessary to describe aspects of tilth by such quantitative terms as clod size distribution and surface roughness which are the result of pulverization.

Dubrovoskii(23) is the first researcher to suggest that tilth is affected by a vibrating tool. He observed that "the length of the cleaved section" is directly related to the wavelength of oscillation. The significance of this observation is the possibility of controlling the resulting tilth to a greater degree than is possible with a rigid tool. This possibility was recognized by Hendrick and Buchele (44).

Gunn and Tramontini (39) observed additional aspects of tilth in their work with vibratory tools. They note that oscillation produces much more fragmentation of the soil than does non-oscillation. Eggenmüller (27) observed superior "crumbling action" and increased inversion of the clods with increased frequency. According to Blight (10), Eggenmüller, in another measure of tilth, obtained an air movement of two to ten times greater through soil tilled with an oscillating tool as compared to a rigid tool.

Stefanelli (86) observed that the proportion of soil particles less than 4 mm in size (fines) is a function of the moisture content and tool vibration. A minimum occurred in the vicinity of 18% moisture content. It may be more than a coincidence that the minimum energy requirement, as noted previously from Fox et al. (32), also occurred at this moisture content. It is of particular interest to notice that the range of the size distribution of fines obtained by Stefanelli (86) is less with a vibratory tool than with a rigid one. Unfortunately the authors do not report any vibration variables nor levels of statistical significance.

Johnson and Buchele (50) specifically investigated the relationship of clod size distribution and the oscillation of a simple tillage tool. Although they conclude that the distribution was influenced by oscillation, the evidence appears to be marginal. On the other hand, the distribution they obtained was greatly influenced by the blade (rake) angle, the soil condition and their interaction. As already noted, Osman (66) found a relation between the rake angle and the distance between the failure surfaces for rigid tools. Coupling Johnson and Buchele's observations with the fact that clod size distribution is only one aspect of tilth, a question can be raised regarding the usefulness of pursuing, at this time, investigations of tilth and vibratory tillage.

Plane of Oscillation

Shkurenko (78) is a Russian researcher who, in spite of Dubrovoskii's prior work, does not report his results on the basis of the wavelength or some dimensionless ratio. He investigated the "cutting resistance" for two planes of oscillation, vertical and horizontal. He noted that the draught of the former was 1.5 to 1.6 times greater than the latter and that both were less than for a rigid tool. He used both a vertical wedge and what appears to be an inclined blade with a rake angle of 45°. With the latter, one would expect rupturing of the soil as well as cutting, but he does not comment on the resulting soil tilth. For this, and other reasons, it is difficult to reconcile his results with that of Eggenmüller.

Venter (92) used a vertical oscillation in his "vibratory plough". Though he did not report his work on the basis of a dimensionless ratio, it appears to be in the order of λ of 3. He obtained a draught reduction of 44 to 49% for soils ranging from sand to heavy clay; all at field capacity. In dry soils, the reduction was in the order of 30%.

Eggenmüller (27) carried out extensive experiments with regard to the plane of oscillation. He obtained a sizeable reduction in draught when the plane of oscillation was rotated out of the horizontal by 15°. He concludes that the angle should be somewhat less than 30°. The effect of the plane of oscillation on the total energy was not reported.

Mode of Vibration

Senator and Warren (76) compared two modes of vibration using a soil concept which they refer to as the modified Coulomb soil model. One of the modes of vibration is the usual arrangement in which ".....motion occurs between the blade and the body of the vehicle so that the vehicle's mass participates in the overall dynamics." As the reaction of the blade's motion is imposed on the vehicle's mass, the authors refer to it as the "participating vehicle plough." In the other mode, the authors conceive an arrangement which has ".... the body of the vehicle isolated from the vibrating blade and its rotating eccentric shaker." The bias or draught force is applied through a large "soft" spring. They term this mode of vibration as the "isolated vehicle plough." Using their idealized soil model with differential equations, the authors computed that the ground speed of the isolated vehicle plough would be approximately three times that of the participating vehicle plough. As the authors were concerned with burial of telephone lines, the operating conditions in relation to conventional tillage were extreme and, on the same basis, the computed ground speeds were extremely low. Their method of analysis could be applied to conventional tillage conditions though it might have to be altered extensively to determine the speed at the optimum total horsepower. In spite of the possible difficulty, this method of investigating vibratory tillage is commendable as it allows for the inclusion of an important design criterion; namely the maximum permissible bearing reaction.

Summary

Some success has been achieved in developing a soil/tool mechanics for rigid tools. It is so limited, however, that there is little inducement, at least for the present, to attempt the development of one for the vibratory tool. In the meantime, dimensional analysis may be an alternative. The dimensionless ratio, λ or its equivalent, contains the main mechanical variables of oscillation and has been used extensively in vibratory tillage studies. In every case there was a correlation between the ratio and the reduction in draught of the tool. On the other hand, unanimity was lacking with respect to the ratio and the total energy required by the tool. This lack may be the result of the observation noted in the prior chapter; namely that the minimum draught may not be coincidental with the minimum energy. There is the suggestion that the critical values of λ are in the range of 0.68 and π. Two other mechanical factors of oscillation have been found to affect the cutting resistance of a tool. In particular there appears to be an optimum plane of oscillation with regard to draught reduction. Soil tilth is also a function of this variable as well as the dimensionless ratio.

CHAPTER 6

FACILITIES

Soil Tank

The experimental work was carried out using the soil tank and other facilities of the National Institute of Agricultural Engineering, Scottish Station (N.I.A.E. - S.S.). The soil tank, which may be seen in Plate 1, was located in a partially enclosed shed. A fully enclosed heated shed would have avoided interruption of the work during the winter, but the lower relative humidity would have complicated the task of maintaining the soil mositure content.

The tank was 6 feet wide by 90 feet long and approximately 2 feet deep. The floor of the tank was the natural occurring soil, which at that depth was mainly an impervious clay. According to Lewis (58), an earth floor has the advantage of more closely approximating the elastic properties of a compacted soil than conventional construction materials such as concrete. The side walls were of brick construction with rails mounted on the top for transport of the tillage cart and power unit. A concrete apron, which extended along one side of the tank, facilitated somewhat the filling and emptying of the tank. Surplus soil was stored in piles alongside the apron.

Power Unit

The self-propelled power unit, which may be seen in Plates 1 to 4, was used to prepare the soil for tillage. It consisted of a bull-dozer blade for levelling the soil and "skimming" it to the desired height, a roller for compacting, and a back-hoe for filling and emptying the tank. Later, a cultivator frame was fitted which replaced the roller when required. A spray boom, pump, and tank were also fitted in order to add water to the soil. Lifting

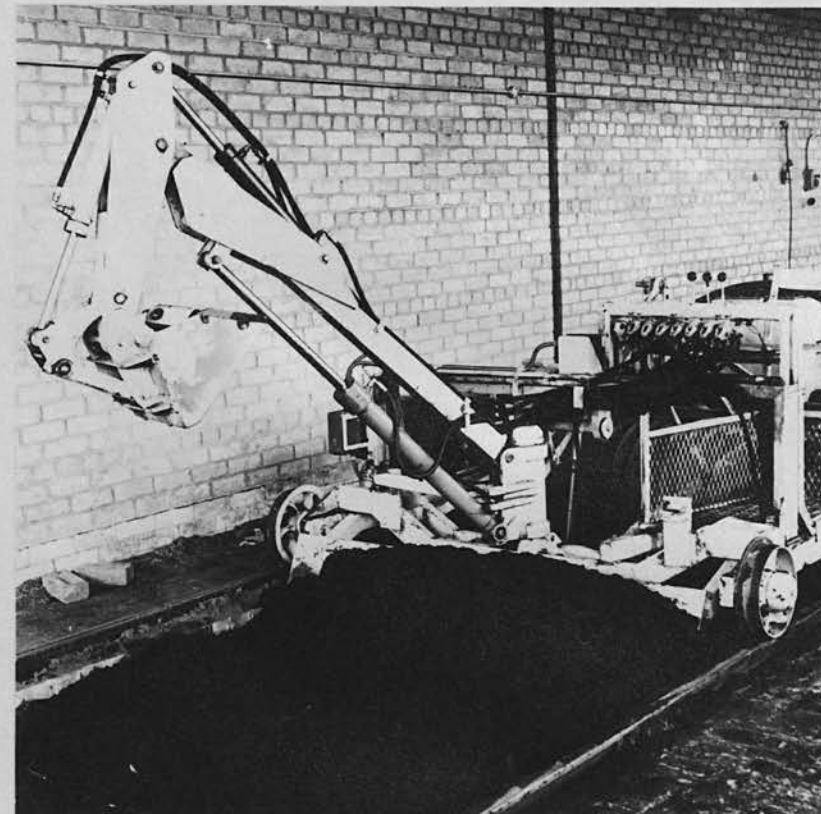


PLATE 1 LEFT - N.I.A.E. S.S. SOIL TANK WITH THE BROWN SOIL IN THE FOREGROUND AND THE RED SOIL IN THE BACKGROUND

RIGHT- LEVELLING THE SOIL WITH THE POWER UNIT'S BULLDOZER BLADE

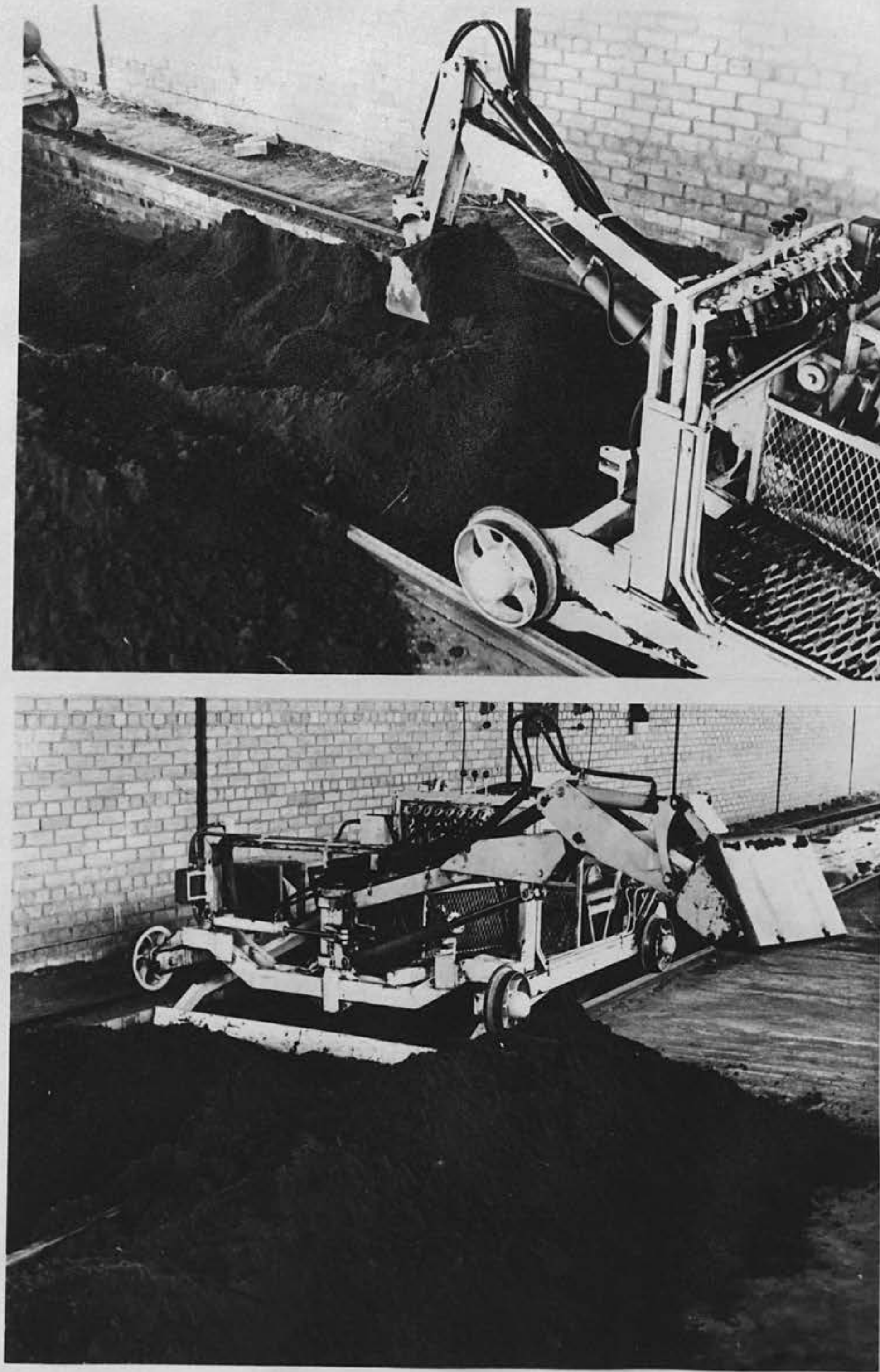


PLATE 2 EMPTYING THE SOIL TANK WITH THE POWER UNIT'S BACK-HOE; TOP - EXCAVATING, BTM - DUMPING THE EXCAVATED SOIL ON THE CONCRETE APRON

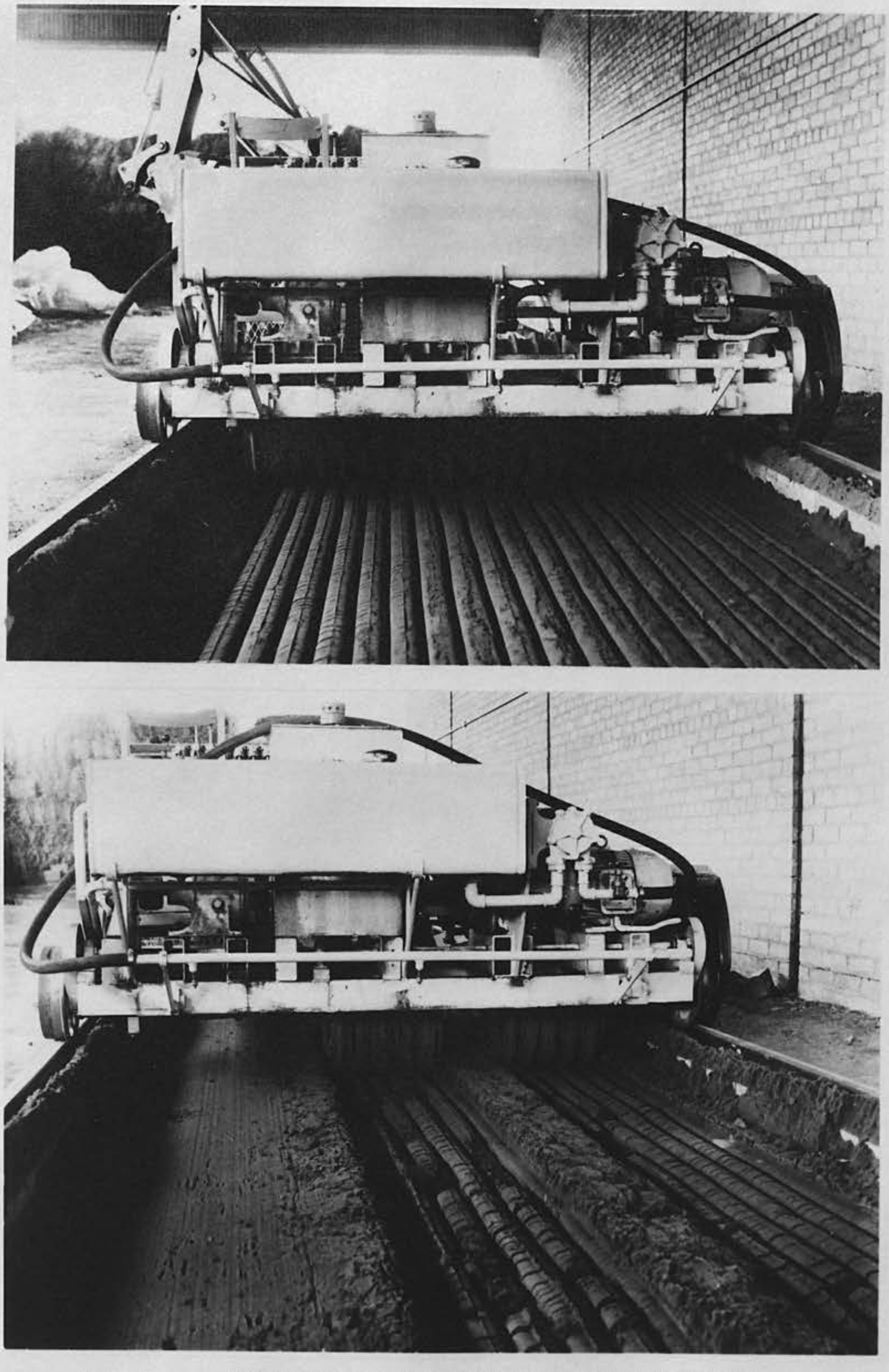


PLATE 3 COMPACTING THE SOIL WITH THE POWER UNIT'S ROLLER; TOP - ROLLER INDEX = 18, BTM - ROLLER INDEX = 60

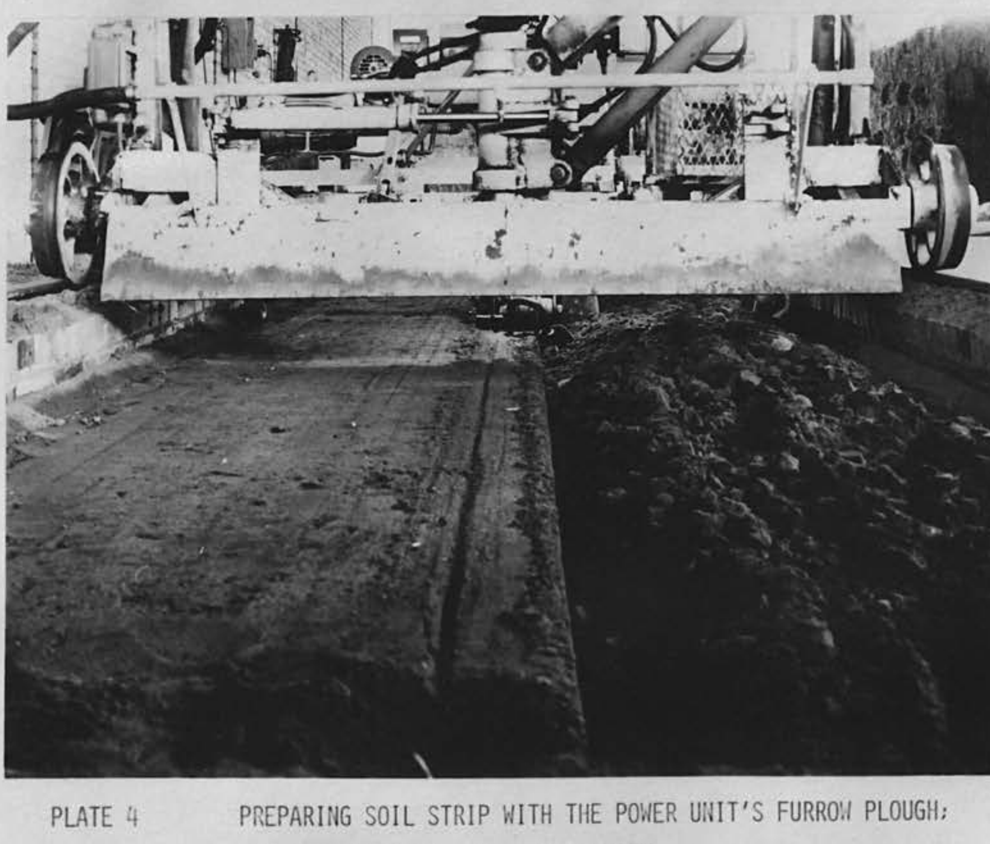


PLATE 4 PREPARING SOIL STRIP WITH THE POWER UNIT'S FURROW PLOUGH; TOP - FRONT VIEW, BTM - REAR VIEW

and lowering the blade and roller, articulating the arms and the bucket of the back-hoe, and propulsion were accomplished hydraulically. The single hydraulic pump was driven by a 7½ horsepower electric motor. Electrical power was supplied through a cable alongside the tank which was wound on or off a reel as the power unit moved along the track. Slip rings maintained the electrical circuit while permitting rotation of the reel.

The hydraulic valves, seven in all (plus an unloading pressure relief valve), were located conveniently on the operator's platform. Though more than one valve could be opened at one time, motion of the rams was so slow and unpredictable that a procedure to activate only one at a time was adopted. The geometry of the back-hoe was such that opening and closing of one valve and then another was required in order to achieve a reasonably level excavation or to clean soil off the apron. With practice, dexterity could be developed to do this rapidly, but for the novice it was a long, tedious task. One exception to the "single valve activation" procedure was in swinging the bucket in and out of the tank and raising or lowering it to clear the tank side and rail. With practice, simultaneous motion in the two planes was possible. Using these procedures, an experienced operator could excavate four inches of soil from one half of the tank and replace it in two-inch compacted lifts in a single day. Complicated compacting procedures and frequent faults, such as bursting of the hydraulic hoses, extended the time required. Difficulty was also experienced in the propulsion system until the control valve was modified to prevent "lock-up" of the hydraulic circuit on stopping. This was causing large momentary torques which sheared keys in the gear box and on two occasions broke the output shaft.

Roller

The fluted cast iron wheels of the roller rotated on a shaft fixed to a frame which in turn was coupled to the power unit by a "three-point linkage" system. Each wheel,weighing 49 lb, was 3 in. wide with an outside diameter of 21 in. Some of these details may be noted in Plate 3. Because of the necessity for the roller frame to fit within the tank, the maximum number of wheels was 21 with a consequent width of 66 in. With this number of wheels, the total weight of the roller, including the frame, was approximately 1180 lb. A guide to the potential compacting performance of a roller is the weight per inch of roller width, referred to hereafter as the roller index. For the roller equipped as above, the index was less than 18 (lb/in.).

In order to obtain a large index, the number of wheels was reduced to 12 and steel billets were added to the roller frame until the total exceeded 1700 lb. This modification increased the index from 18 to 45. Reduction in the number of wheels was required because the maximum lifting capacity of the power unit was between 1900 and 2000 lb. To prevent the roller from tipping, in the lateral plane, the wheels were put into two groups of six with a 12 in. spacer between them. The wheels were shifted 15 in. in one lateral direction or the other, after making a suitable number of passes, in order to compact the full width of the soil tank (66 in.). The spacing and the amount of shift provided an overlap of the compacted ruts. The overlap seemed desirable because the soil bulged upwards on either side of the initial ruts.

To increase the index even further, the number of wheels was reduced to 10 and ballast added until the total weight approached the maximum lifting capacity of the power unit. The roller index for this modification was approximately 60. As can be seen in Plate 3, the wheels were put into two groups of 5, spaced 9 inches apart. In this case, they were shifted 12 inches rather than 15. With only one shift of the wheels per lift of compacted soil, the full width of the tank could not be treated. This, however, was not required as the lateral positioning of the vibratory drive was limited to slightly more than half the tank width.

One final point with regard to the roller was a problem of soil adhesion. This occurred on the ridge or apex of the wheel as the soil firmed with subsequent passes. The adhesion was apparently a function of the contact pressure which was maximum when the ridge only partially penetrated the soil and the wheel, in the lateral plane, was not fully in contact with the soil. At times the soil would bridge between the wheels and long sections, slightly more than one inch deep, were lifted and deposited elsewhere in the tank. This can be seen in Plate 3. For the small roller index, transport of the soil was minimized by levelling the soil between passes and by coating the wheels with a non-wettable material. With regard to the latter, a number of commercial products were available, but as Gill and Vanden Berg (37) wrote, "Lack of abrasive resistance is the biggest drawback to non-wettable materials." The commercial release agent used was Releasil 2540 manufactured by Midland Silicones Limited.

It was not feasible to level the soil between passes when less than the full tank width was compacted. The ruts would have been filled with each pass and this would have resulted in either a large variation in soil height or density. Though adhesion and lifting of the soil could not be prevented, scrapers were added so that the soil lifted by the wheels was not transported to one end of the soil bed or the other. After compacting the final lift, the disturbed soil was skimmed off with the blade of the power unit.

Furrow Plough

It was necessary to prepare the soil in strips for the second part of the experimental work in order to use a horizontal tool. To avoid the soil reaction of the shank, a furrow was required. By cutting the soil to a similar depth parallel to the furrow, pulverization of the soil was restricted in a manner recommended by Gill and Vanden Berg (37). The procedure in using this device or furrow plough was to prepare one soil strip which was subsequently tilled before preparing another. In this way, the maximum use of the compacted soil in the tank was obtained. The furrow plough consisted of two rolling disk coulters, one with a skim or jointer which were mounted in a sub-frame which in turn was mounted on a cultivator frame. Details may be seen in Plate 4. The cultivator frame replaced the roller on the power unit for this task. The sub-frame could be fixed at one-inch intervals in the lateral plane. The orientation of the jointer was altered from the normal position when used on a mould board plough. Gauge wheels were added to control the depth, but more importantly, to aid in maintaining the coulters in the vertical plane. Their effectiveness was limited because of the necessity to locate them close to the tank walls where the soil was uncompacted. This limitation contributed to much of the difficulty experienced in maintaining the lateral position of the plough with respect to the tank walls.

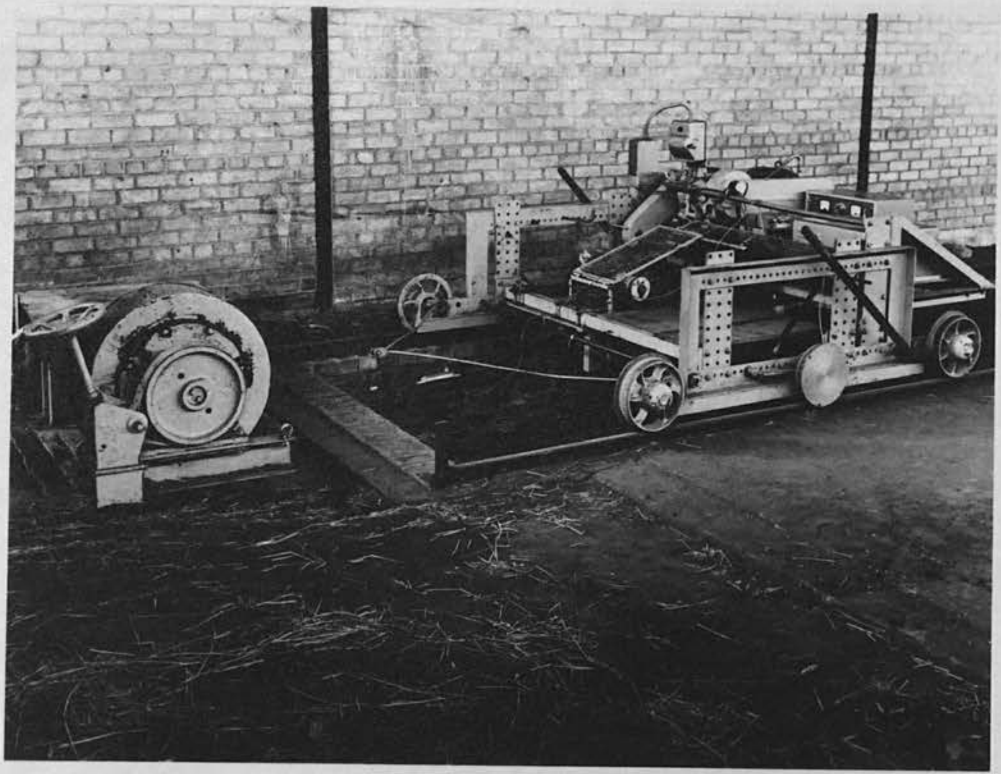
With slight tilting of the coulters, a lateral soil reaction caused the coulters to pivot about their respective vertical posts until a new equilibrium was established. In other words, tilting the coulters out of the vertical caused them to rotate out of the plane of travel. This action had two serious consequences. Firstly, precise control of the lateral position of the plough was unobtainable. Secondly, the soil reactions were perpendicular to the plane of the coulter. When the coulter was tilted out of the vertical, the soil reactions were tilted out of the horizontal. This caused compaction on one side and soil dilution and, therefore, loss in soil strength on the other. Preventing the coulters from swivelling about their vertical posts improved the performance of the plough in both respects. It was necessary, however, to add "slippers" close to the coulters to eliminate all soil dilution. The "slippers" imposed a downward pressure on the soil surface which offset the lateral pressure produced by the coulters. With the exception of the dense red soil, the function of the plough with these modifications was satisfactory.

The difficulty in the dense red soil was essentially the first mentioned problem that occurred previously when the coulters were free to pivot about their vertical shafts; namely the lack of control of the plough's lateral position. In this case, the lateral pressure was sufficient to cause the cultivator frame to move sideways relative to the power unit. It was found necessary to "steer" the plough by tilting the frame of the cultivator, first in one direction and then in the other. The adjustment was part of the "three-point linkage" system of the power unit and which was used previously to level the frame of the roller. Control of the lateral position in the dense red soil was, at best, marginal. On occasion the strip width narrowed to nearly 4 inches from the maximum of 5. This likely caused much of the variation that occurred in the experimental results in this particular soil. One final modification was to add a concave disk as an aid in obtaining a wide enough furrow for the shank.

Tillage Cart and Winch

A cart, on which the vibratory drive, tillage tools, and instruments were mounted, was pulled along the tank rails by a winch. This may be seen in Plate 5. The instruments and vibratory drive are discussed later. The winch, which was located at one end of the soil tank, was driven by a 4 horsepower electric motor through an epicyclic gear and a hydraulic type, variable speed transmission. The latter provided for adjustment of the cart velocity. The winch could be engaged by applying a brake band in the epicyclic gear drive. Though engaging the winch in this manner gave reasonably uniform acceleration of the cart, it took too long to bring the cart up to the required velocity. Engaging the brake band and then starting the drive by switching on the electric motor was the alternative. The difficulty with this procedure was that the mass of the cart, when fully equipped and with an operator, was large. The cart would "over-run" the winch cable and, as a result, its motion was a series of jerks, even with the tool in the soil. A set of tension springs between the winch cable and the cart attenuated somewhat the velocity variation. The number of springs and their size was determined on a trial and error basis. The final arrangement may be seen in Plate 5. The short chain prevented the transducer from dragging on the ground when there was no tension in the cable.

The most useful modification to the cart was the addition of a set of hand-operated brakes. Later a lever was added so that they could be locked in the engaged position. With the brakes so engaged, all of the cable slack could be removed. Once the cart was in motion the lever was unlocked and the brake pressure reduced until the tool entered the untilled soil. In order to do this, it was necessary to re-position the cart so that it "over-ran" the prior-tilled soil. The brakes were also found useful in preventing "over-runs" when the winch drive was shut off and providing a "safety-feature",



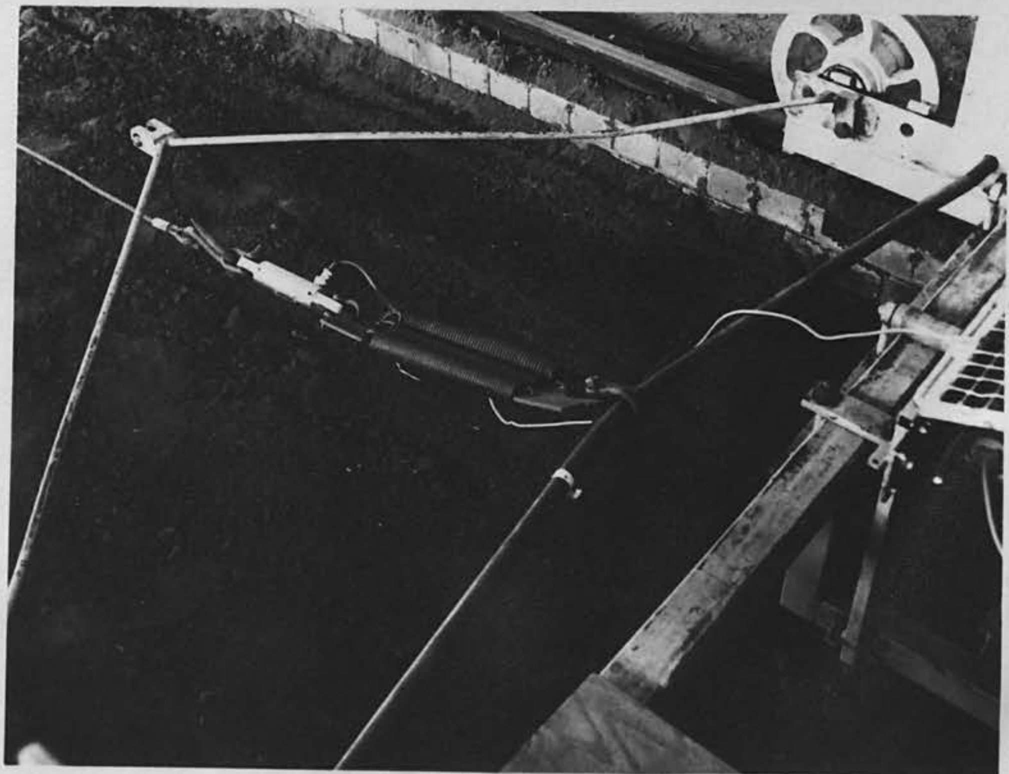


PLATE 5 TOP - TILLAGE CART AND WINCH
BTM - DRAUGHT TRANSDUCER AND ATTENUATION SPRINGS

particularly when the cart approached the end of the soil tank and the winch.

Even with these modifications, variations in the cart velocity occurred during the run. The final solution was to select a time interval in such a way that the cart velocity was the same at the end as at the beginning of the interval (see Data Processing and Analysis).

Vibratory Drive

Oscillation was obtained by a slider/crank mechanism (see Figure 6 and Plate 6). The connecting rod of the crank was attached to one end of the rocker and the other end of the rocker was attached to the tool holder or shank. The latter was guided in a single plane by two pairs of "sliding" bearings. A pair of tension springs were fitted to the shank part way through the experimental work to reduce the inertia reaction caused by oscillating the mass of the shank and tool. The pivot point of the rocker could be adjusted relative to the ends, providing for adjustment of the amplitude of oscillation. The crank was driven by an electric motor through a hydraulic type variable speed transmission. The latter provided for adjustment in the frequency of oscillation.

The bushings of the crank and rocker-mechanism bearings, and also the "sliding" bearings, were bronze. For large bearing pressures, bronze bushings are usually the most satisfactory design but the inability to maintain a consistent level of lubrication undoubtedly contributed to the variation in the torque results. Four "V" type drive belts were required, one of which connected the motor and transmission (see Figure 6). The other three had to do with positioning of the tool and are noted below. The original 4 HP electric motor was replaced by a larger 7½HP as the former stalled when the amplitude and frequency were large.

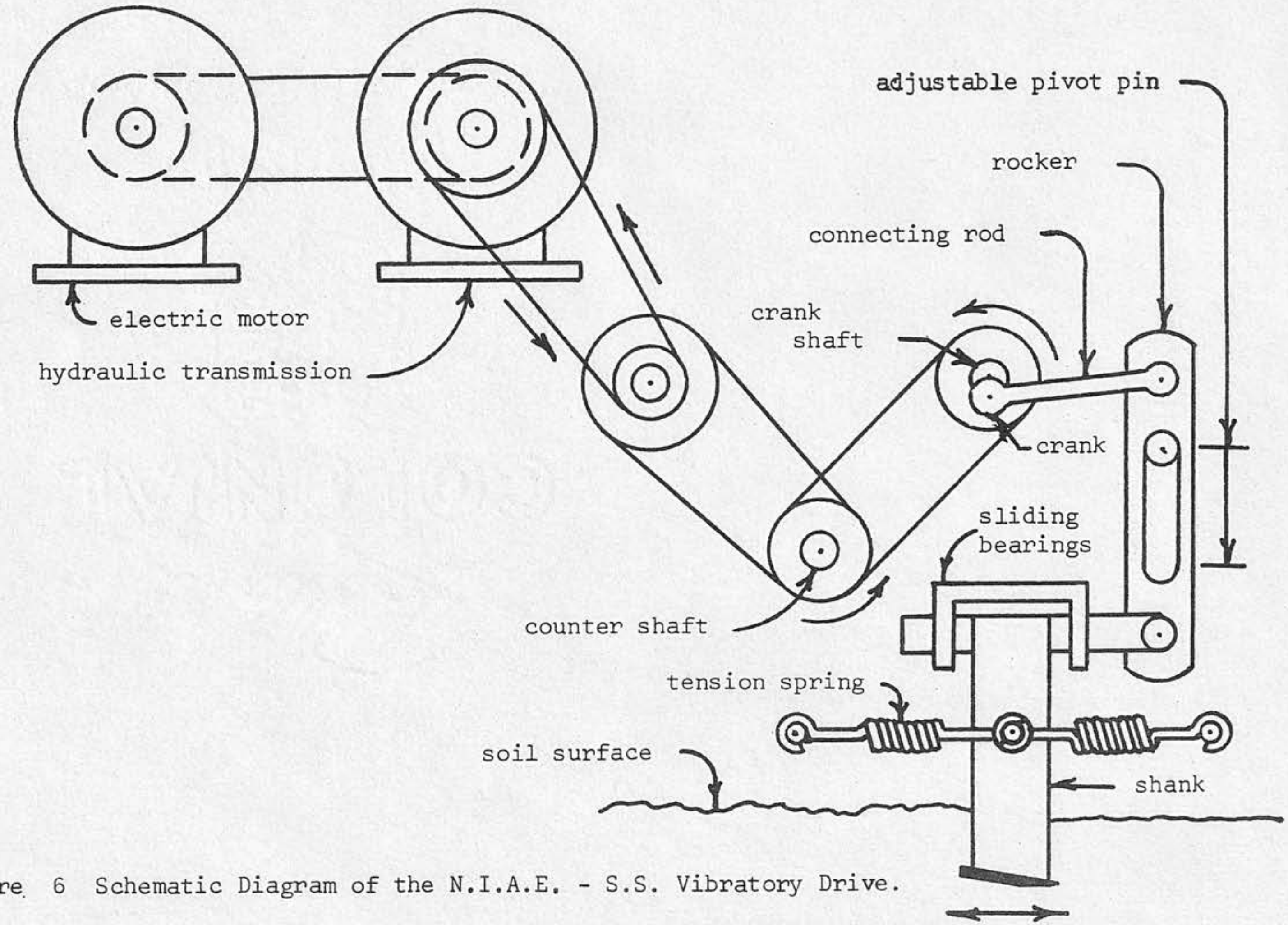


Figure 6 Schematic Diagram of the N.I.A.E. - S.S. Vibratory Drive.

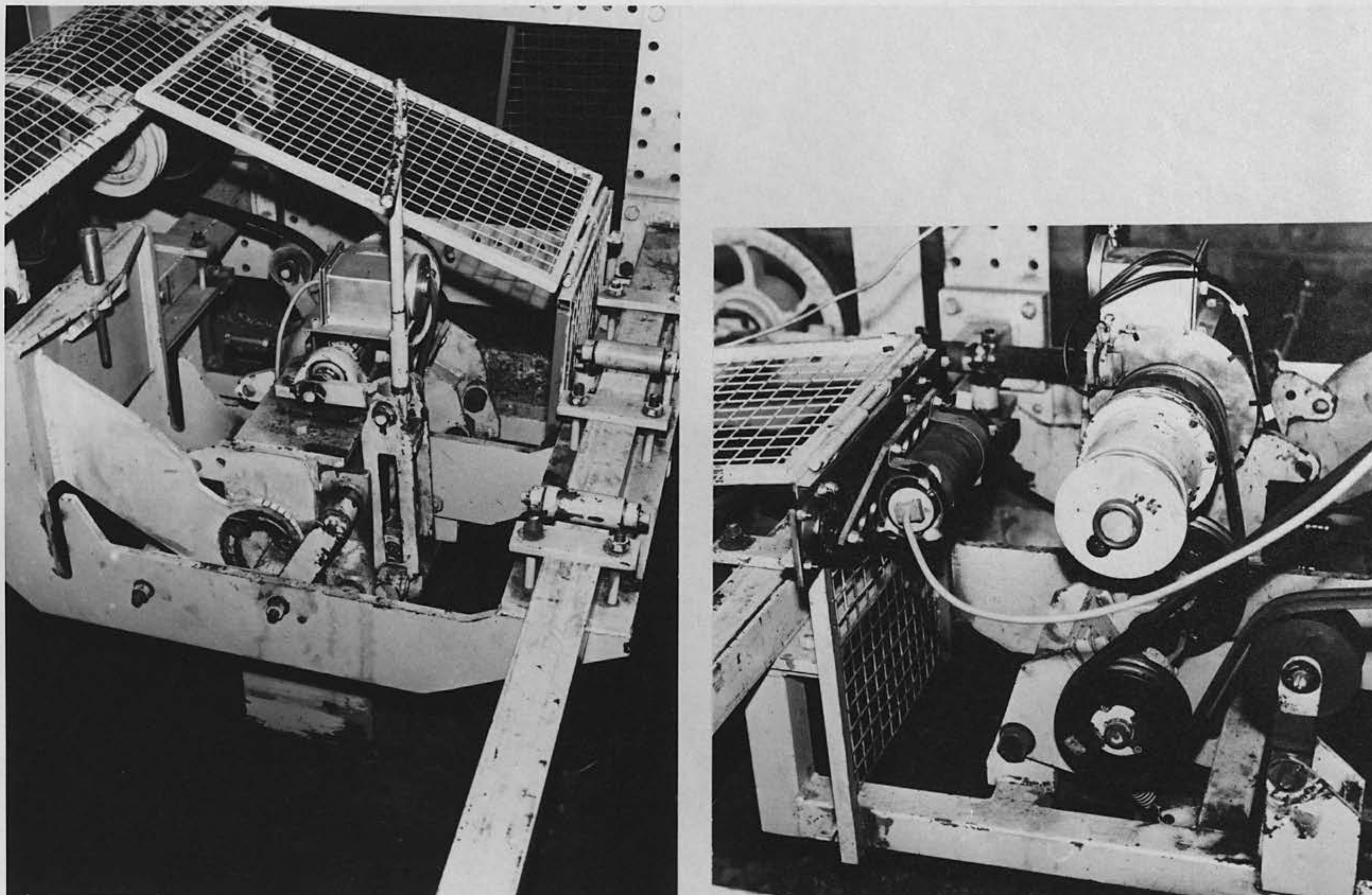


PLATE 6 LEFT - VIBRATORY DRIVE WITH VERTICAL TOOL
RIGHT- TORQUE AND FREQUENCY TRANSDUCERS

The crank and rocker mechanism, along with the tool and shank, were mounted on a frame which in turn was attached to a sub-frame of the tillage cart. The frame was attached to the sub-frame with two pairs of non-parallel links. This linkage not only provided for rotation of the plane of oscillation out of the horizontal but the geometry was such that, if the rotation was positive*, the vertical variation of the bottom leading edge of the tool was less than if a simple pivot was used. Minimum variation occurred when the leading edge was in line with the two attaching pivot centres on the frame.

The maximum positive rotation, or inclination of the plane of oscillation, was 40°. Originally, the inclination was adjusted by a screw and linkage system but, due to its flexibility, the frame oscillated rather than the tool. Providing a rigid but adjustable connection was difficult because of the magnitude of the acceleration of the shank and tool and the location of its centre of gravity relative to the "sliding" bearings. The resulting couple was large and it reversed for each cycle. A friction clamp was fitted but this was later augmented by an adjustable strap. The former was found inadequate when the couple was increased substantially by the druaght of the tool.

Two of the belt drives noted above were associated with the provision to alter the plane of oscillation. To maintain belt tension, the centre line of the counter shaft and the frame's axis of rotation must

* Eggenmüller (27) defined positive rotation of the plane of oscillation or "directions of oscillation" if, as a consequence of rotating the plane, the tool moves obliquely downwards while moving forward.

coincide or nearly so. The other belt drive was required for a shaft that extended across the cart. This enabled the crank to be driven regardless of the tool's lateral position.

The sub-frame of the cart was mounted on two horizontal square bars extending from one side of the cart to the other. Positioning of the sub-frame, and therefore the tool, could be fixed in any position within limits in the lateral plane by a clamping arrangement to the bars. The rollers of the sub-frame reduced the force required to shift it when it was not clamped.

The vibration at maximum frequency and amplitude was extremely severe. Even at intermediate values it caused serious problems. All cap screws and nuts on bolts in the vibratory drive frame and sub-frame required lock washers and it was desirable to "double-nut" wherever possible. In spite of these precautions, the bolts which attached the crankshaft bearing blocks to the frame would loosen and plates had to be welded on to the sub-frame to prevent movement of the blocks. Because of wear, new rocker pivot bearings were required between the first and second part of the experimental work. A list of all the mechanical failures is too long to be included. The difficulties experienced, however, are indicative of the problem in designing a commercially reliable product for use on the farm. Grief was also experienced with the instrumentation because of the vibration.

Vibratory Drive Friction

The relationship between the shaft horsepower and λ (or z') in the experimental work was found to be of the same order as that obtained by Eggenmüller (27), (see Figure 5). Though he suggests that the friction in his vibratory drive was large, he associates any change in the power required with tillage of the soil, which in turn was a function of the frequency and amplitude of oscillation. The implication is that the friction in his drive was constant or nearly so. This was not the case for the drive used in the experimental work. That is, for valid results, it would be necessary to determine the proportion of the torque associated with the drive friction.

The torque required to oscillate the tool without engaging the soil was obtained while varying the frequency. For convenience, this is referred to as the "frictional" torque. The "frictional" torque/frequency relationship (see Figures 7 to 12) was obtained for two amplitudes and two tools, of which one tool was with and without the springs noted in the prior section. These relationships*, besides illustrating the variations in the "frictional" torque, were to be used later to estimate the proportion of the input torque associated with tilling of the soil. For convenience, this proportion is referred to as the "load" torque. The basis for this proposed calculation is that the "frictional" and the "load" torque are additive. This follows from the conservation of energy, which in this case can be stated as:

work in = work out + losses (frictional).

It was unexpected that, at the maximum frequency, the "frictional" torque was greater than the input torque while tilling the soil. Apparently the "frictional" torque was not only a function of the frequency and amplitude of oscillation, but was also a function of the "load" torque. In view of this, an attempt was made to determine the magnitude of the "load" torque at the maximum frequency, and preferably, to find a criterion for calculating it from the input torque recorded during the experimental work.

The first endeavour was to add additional springs to eliminate the

* The data was plotted directly from the punched paper tape and, therefore, a table of the observations is not available.

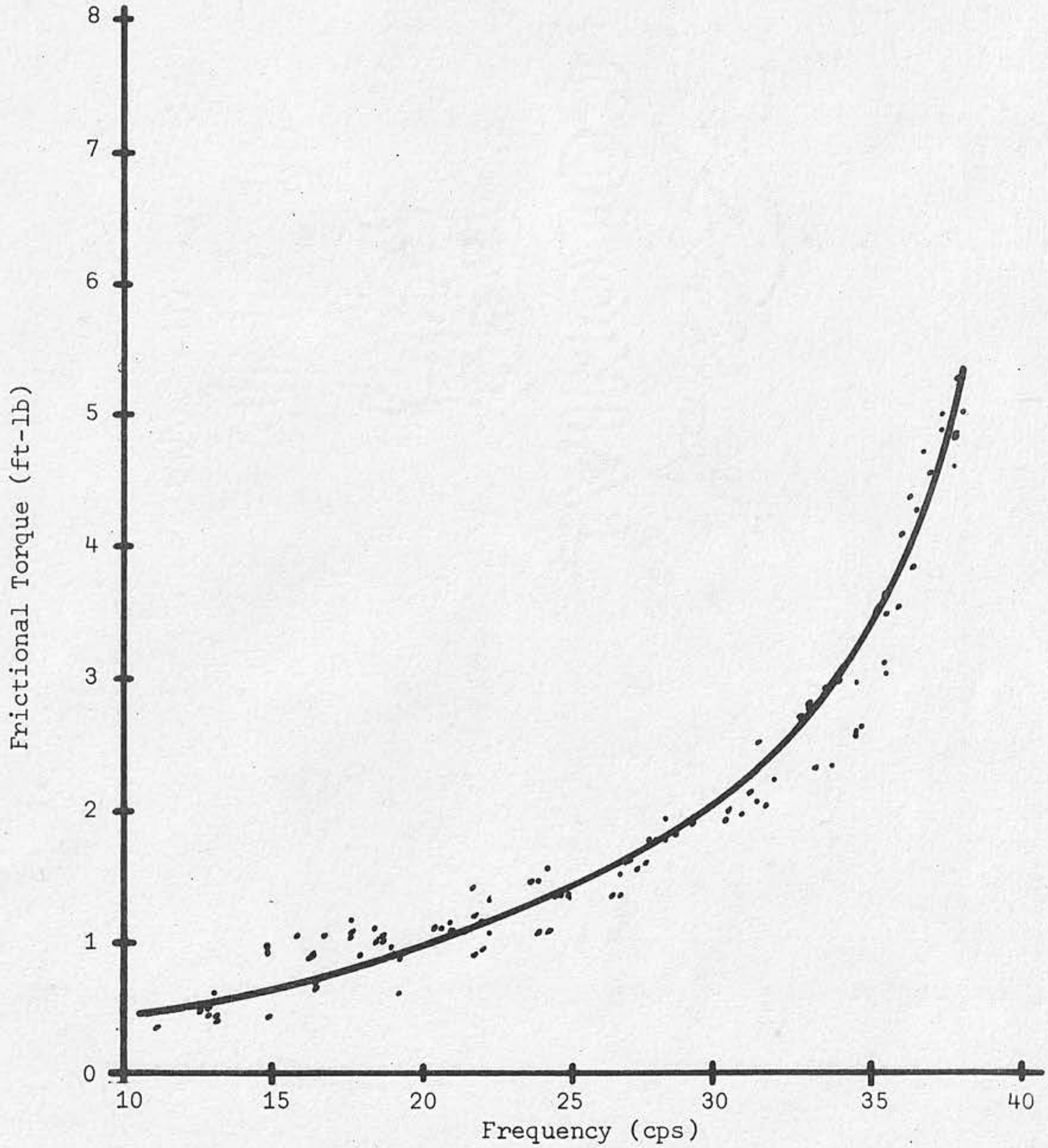


Figure 7 Frictional Torque/Frequency Relationship of the Vertical Wedge; nominal amplitude = 0.012 ft.

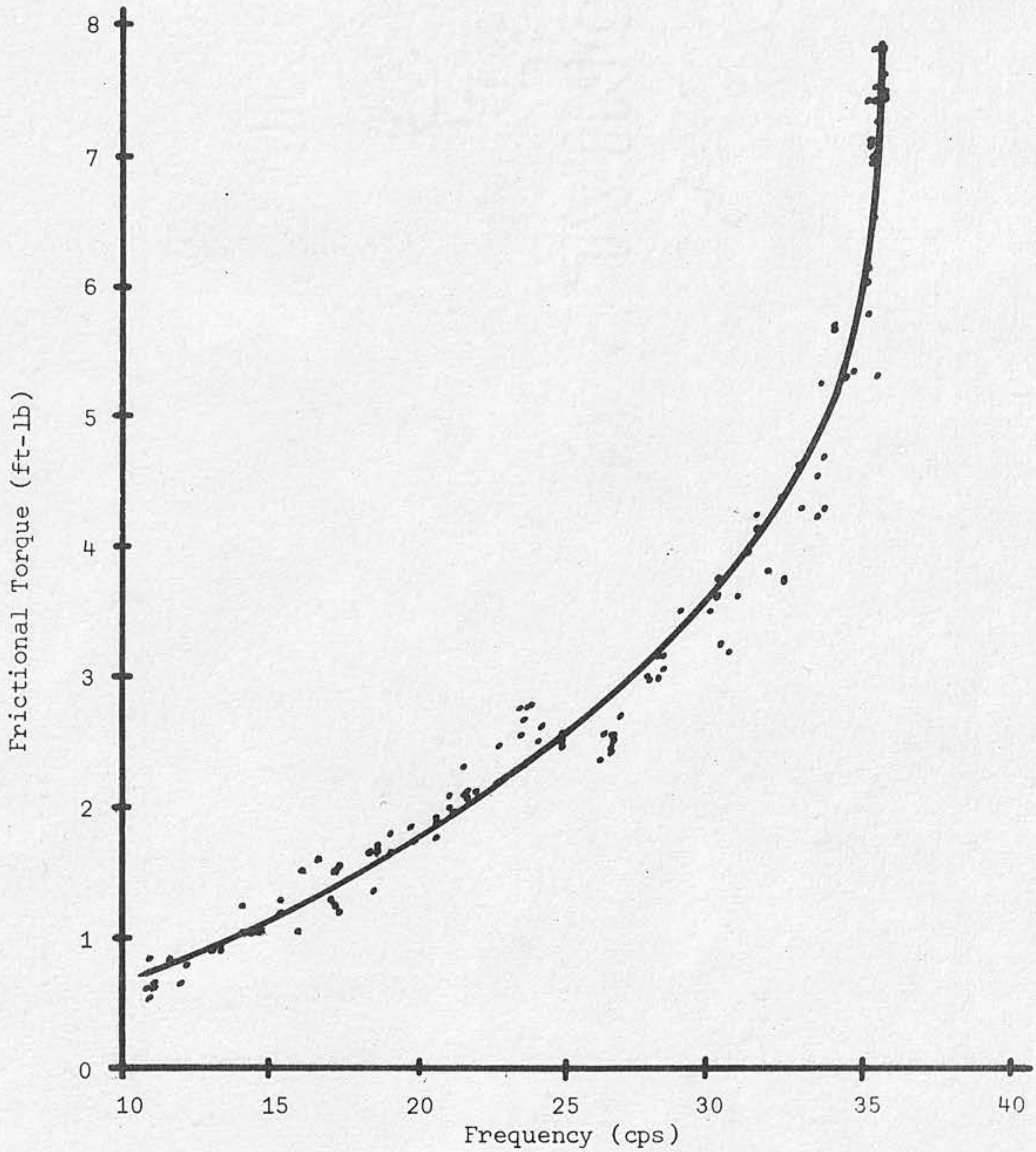


Figure 8 Frictional Torque/Frequency Relationship of the Vertical Wedge; nominal amplitude = 0.018 ft.

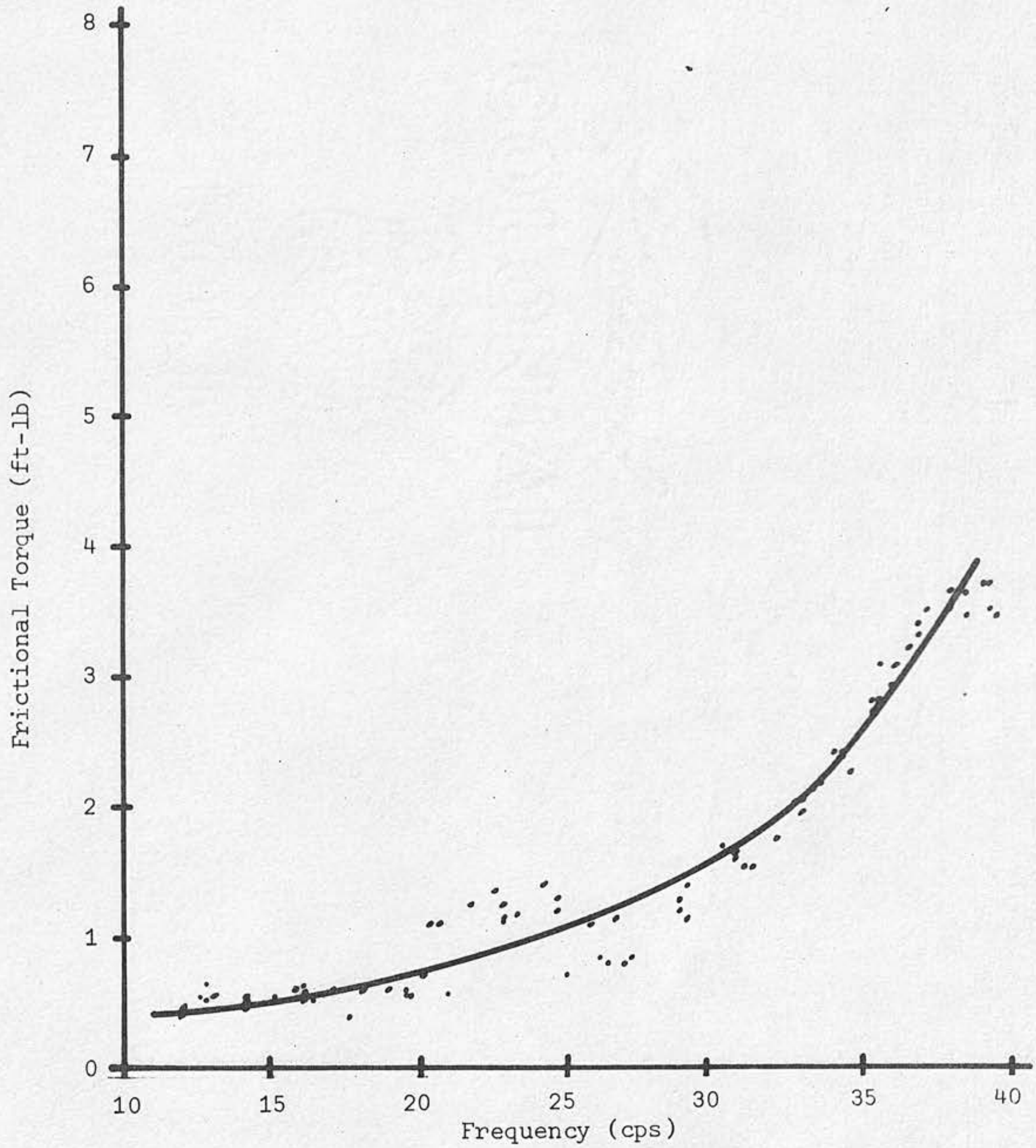


Figure 9 Frictional Torque/Frequency Relationship of the Horizontal Tool; nominal amplitude = 0.010 ft.

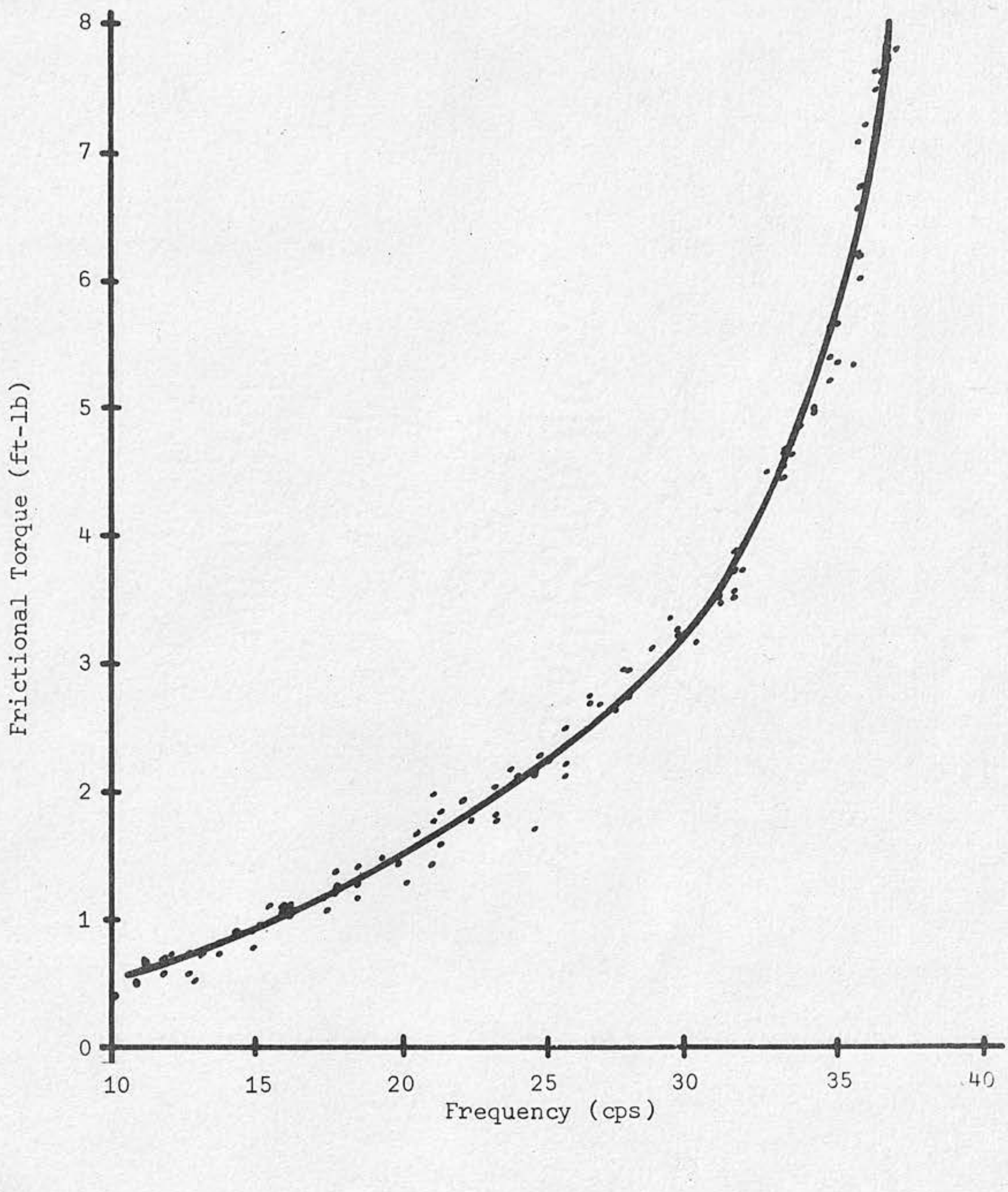


Figure 10 Frictional Torque/Frequency Relationship of the Horizontal Tool; nominal amplitude = 0.020 ft.

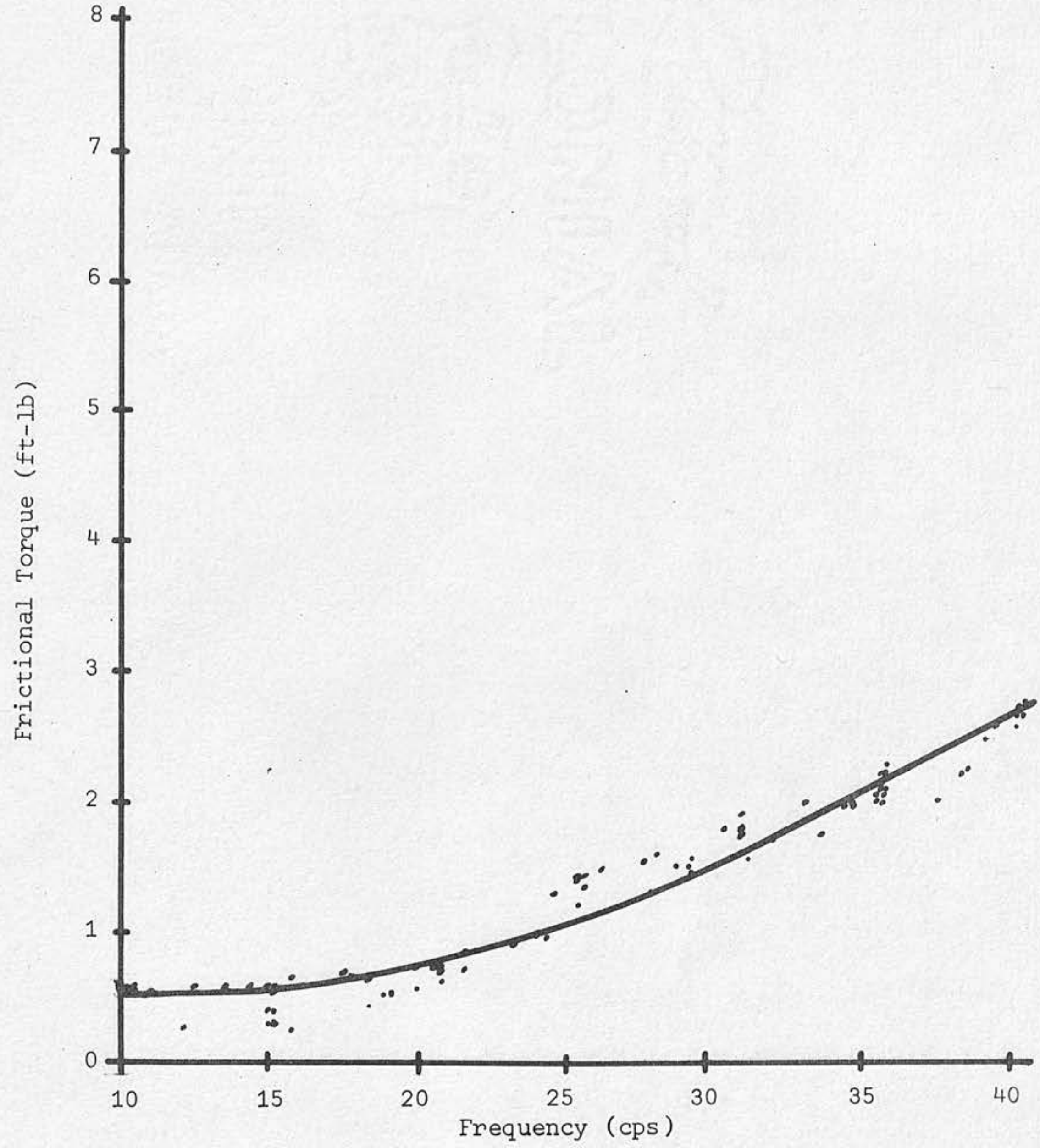


Figure 11 Frictional Torque/Frequency Relationship of the Horizontal Tool; nominal amplitude = 0.010 ft, with tension springs.

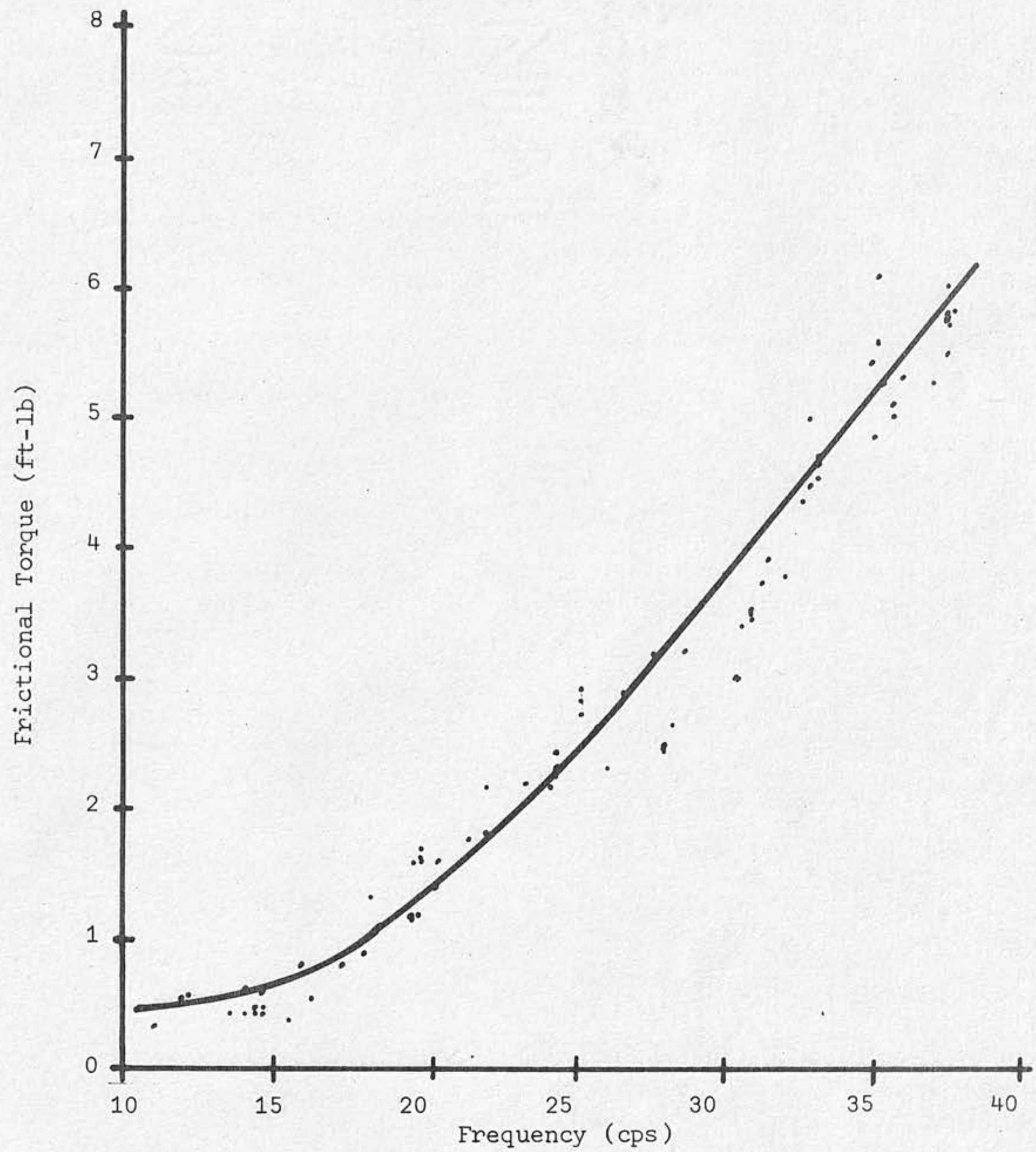
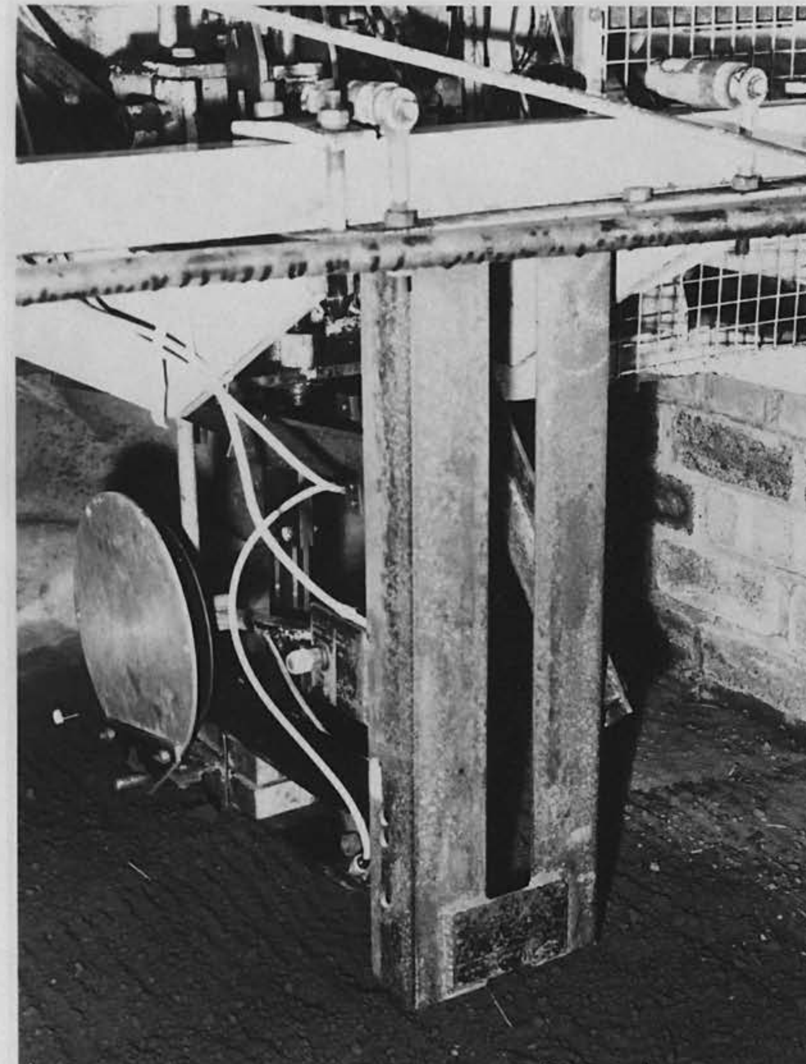


Figure 12 Frictional Torque/Frequency Relationship of the Horizontal Tool; nominal amplitude = 0.020 ft, with tension springs.

action forces (and therefore, the "frictional" torque) required to oscillate the mass of the shank and the tool at the maximum frequency. One additional set, however, caused the arms to which the springs were fixed to oscillate at a frequency below the maximum frequency. This caused "nodes" to occur in the input torque, depending on whether the frequency was either in-phase or out-of-phase with the natural frequency of the arms. Because an additional two sets of springs would have been required in order to eliminate the action forces at the maximum frequency, a major redesign of the vibratory drive frame was needed to accommodate arms with sufficient rigidity. In view of this, it was necessary to abandon this course of action.

The next endeavour was to obtain a direct measurement of the "load" torque and its relationship with the input torque. For this purpose two wooden blocks were clamped so that a frictional load (not to be confused with the "frictional" torque in the drive) could be applied to a horizontal projection of the shank. The two blocks were fixed to the frame of the cart through the draught transducer (see Transducers). The clamp may be seen in Plate 7 along with the associated instrumentation. The frictional load was increased by increasing the spring pressure on the clamp. It was immediately obvious that, as the frictional load was increased, the amplitude of oscillation of the tool was decreased. This was the most important observation of the investigation because the phenomenon was not, and in fact could not be, seen while tilling the soil.

It is apparent that the change in amplitude was caused by the action force and the inertia of the shank forming a couple. This was maximum at the end of each stroke. The couple was in equilibrium with a pair of reaction forces which were applied to the shank at the "sliding" bearings. The location



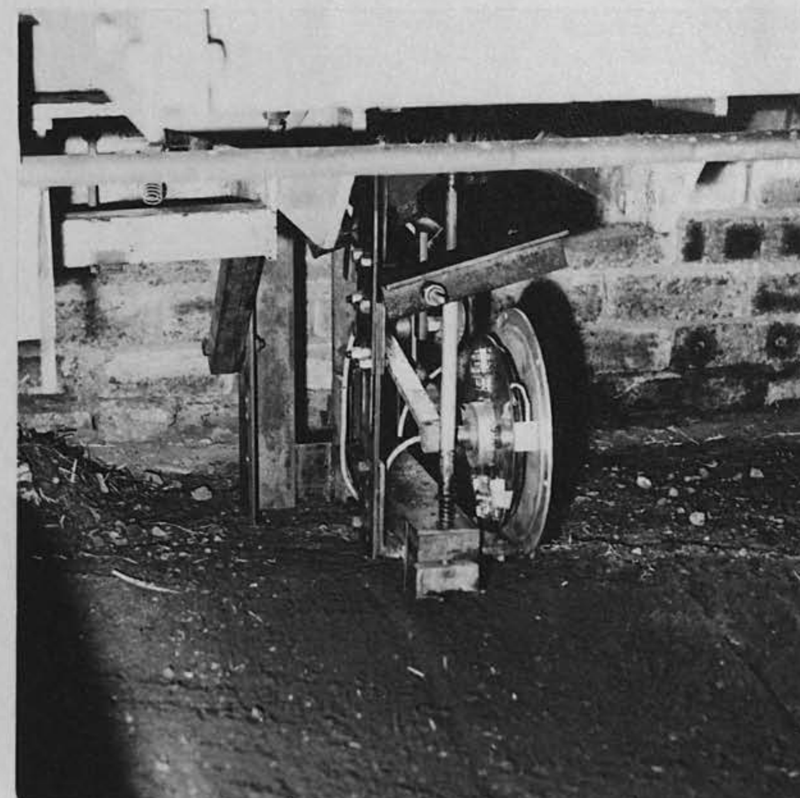


PLATE 7 FRICTION CLAMP AND VELOCITY TRANSDUCER; LEFT - FRONT VIEW, RIGHT - REAR VIEW

of those bearings was such that clearance in them resulted in a rotation of the shank in the vertical plane and which had the effect of increasing the amplitude of the tool. It appears that the frictional load, or the soil resistance, reduced the couple, reducing the amplitude of oscillation, which in turn reduced the "frictional" torque. While tilling the soil at the maximum frequency, the reduction in "frictional" torque must have been greater than the increase due to the "load" torque.

The implications of this phenomenon with respect to the tool displacement are noted in Chapter 8. At this point it is sufficient to observe that it now appeared necessary to measure the amplitude of oscillation as the frictional load was altered. For this purpose the speed transducer (see Transducers) was attached to the horizontal projection of the shank. The relationship of the average velocity of the tool and the amplitude is as follows;

$$V = 4Af$$

where V is the average velocity of the tool,

f is the frequency of oscillation, and

A is the amplitude of oscillation ($\frac{1}{2}$ peak to peak), or

$$A = V/4f.$$

The average velocity of the tool was obtained by integration. This was no problem for the speed transducer as it provided a positive signal for either direction of rotation. For the draught transducer (when attached to the wooden blocks) this was not the case. It was necessary to block the negative signal electronically, otherwise the integration of the frictional load would be zero. The "load" torque was determined by assuming that the frictional force applied by the draught transducer was equal for either direction of motion. The relationship between the frictional load and the "load" torque is as follows:

$$\text{work/cycle} = 2\pi t, \text{ or}$$

$$\text{work/cycle} = (4A)(2F) = 8AF$$

where t is the "load" torque, and

F is the frictional force in one direction.

Therefore,

$$t = 4AF/\pi.$$

Substituting for A,

$$t = VF/\pi f.$$

The relationship of the frictional load, F, and the tool velocity, V, (or tool amplitude, A) was determined for the maximum frequency of 37½ cps and the nominal amplitude of oscillation of 0.020 ft. The other variables were; (a) with and without the springs, and (b) with the plane of oscillation horizontal or tilted. The latter was required because the location of the soil reaction with respect to the "sliding" bearings was altered when the plane of oscillation was changed. For the investigation, the plane of oscillation remained horizontal and only the horizontal projection of the shank was relocated.

As can be seen in Figures 13 to 16,* the relationship of F to V was affected by the location of the horizontal projection of the shank (plane of oscillation), but not extensively by the addition of the tension springs. Much of the scatter of the plotted points occurred because of the manner in which the clamp was adjusted to increase or decrease the frictional load. In spite

* As in the prior case, the data was plotted directly from punched paper tape and, therefore, no table of observations is available.

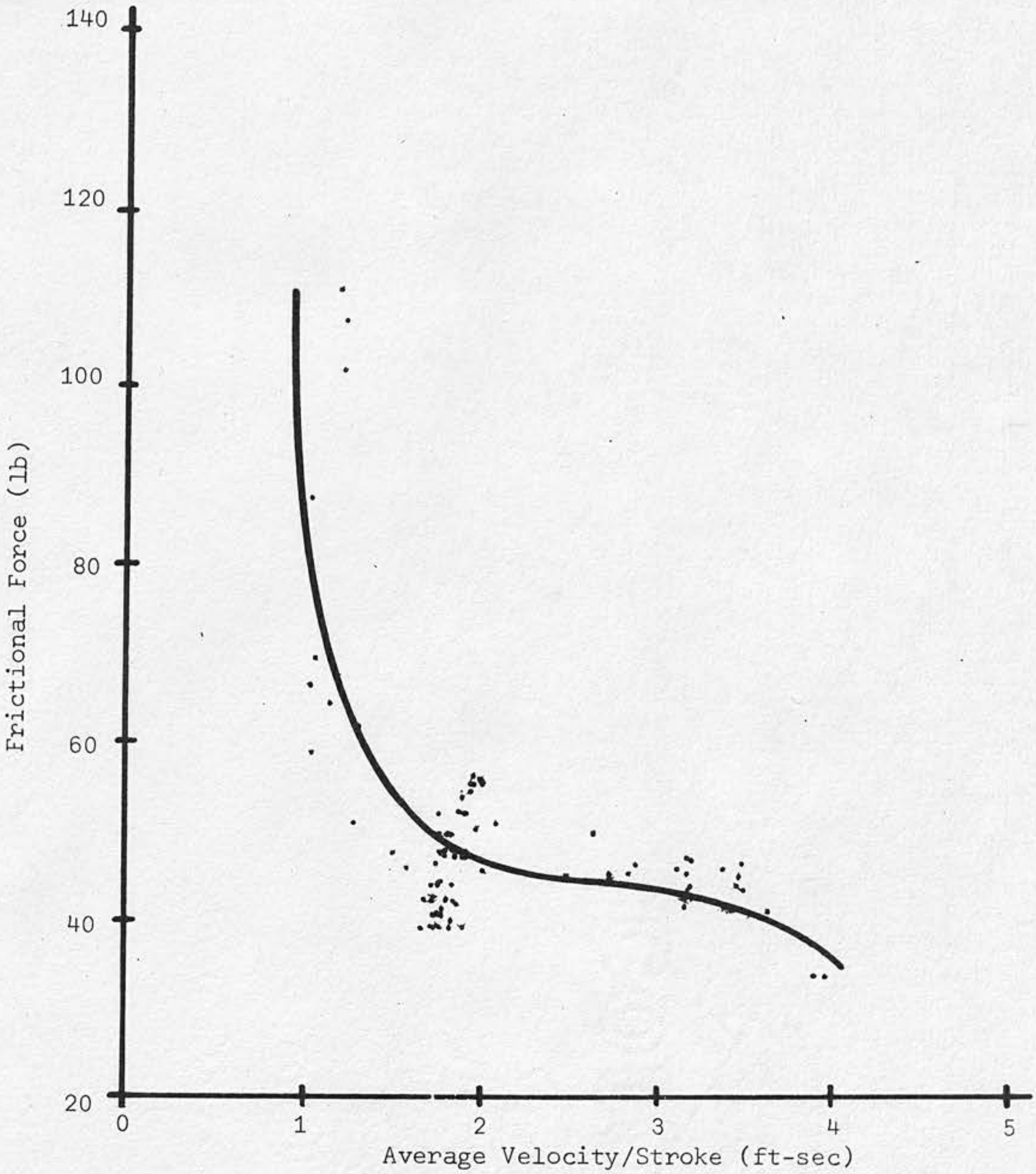


Figure 13 Frictional Force/Tool Velocity Relationship; nominal amplitude = 0.020 ft, horizontal plane of oscillation.

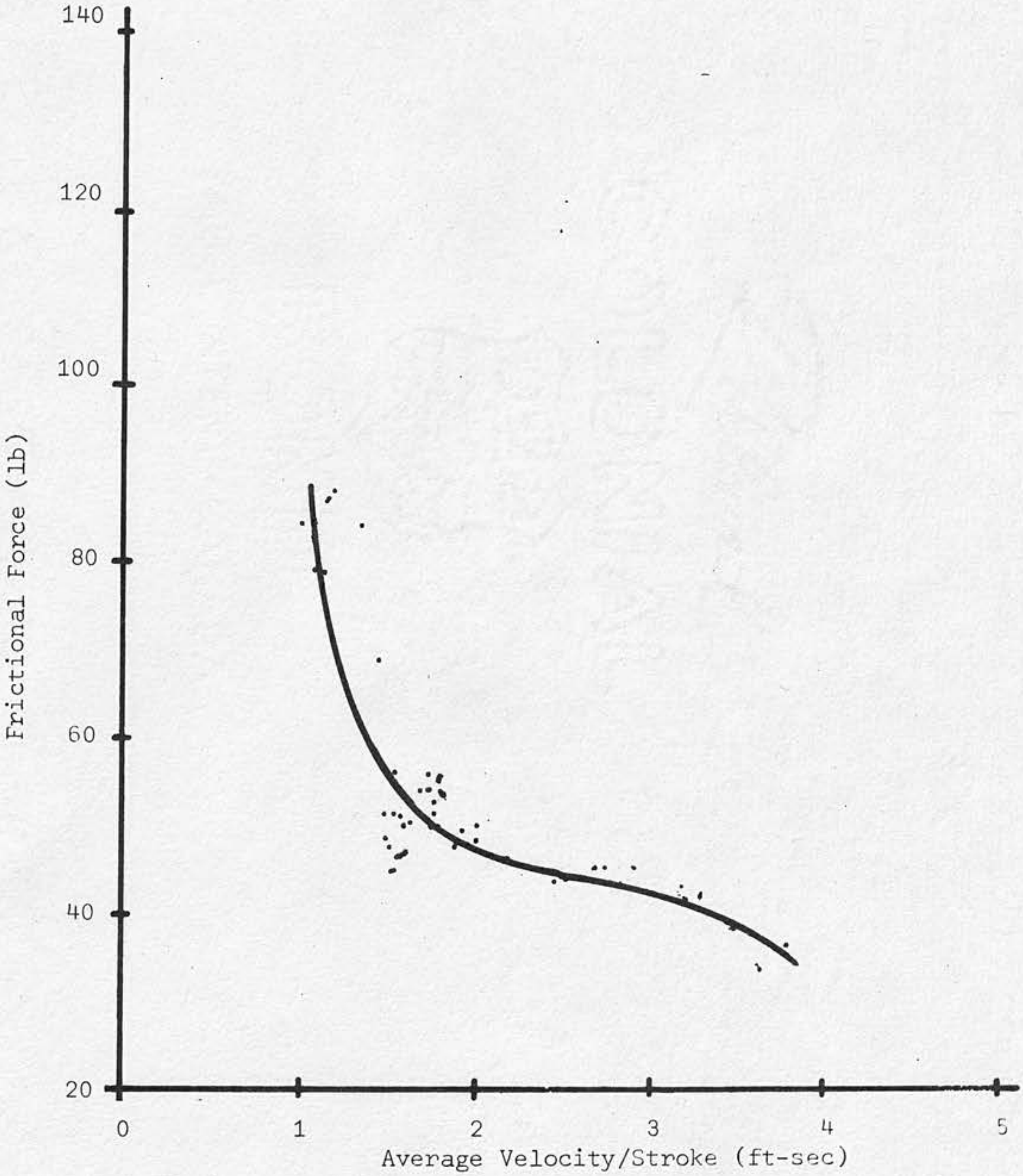


Figure 14 Frictional Force/Tool Velocity Relationship; nominal amplitude = 0.020 ft, horizontal plane of oscillation with tension springs.

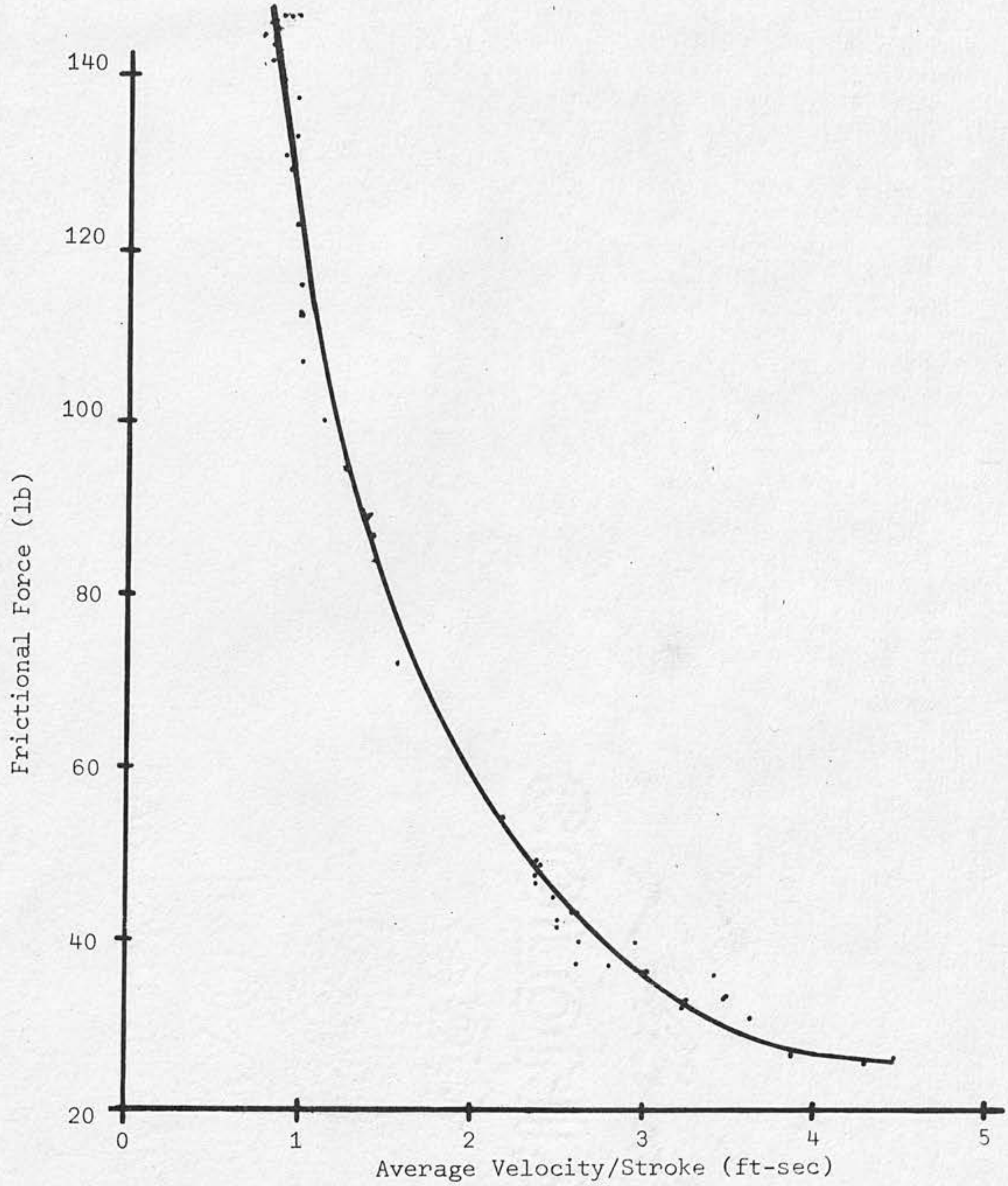


Figure 15 Frictional Force/Tool Velocity Relationship; nominal amplitude = 0.020 ft, tilted plane of oscillation.

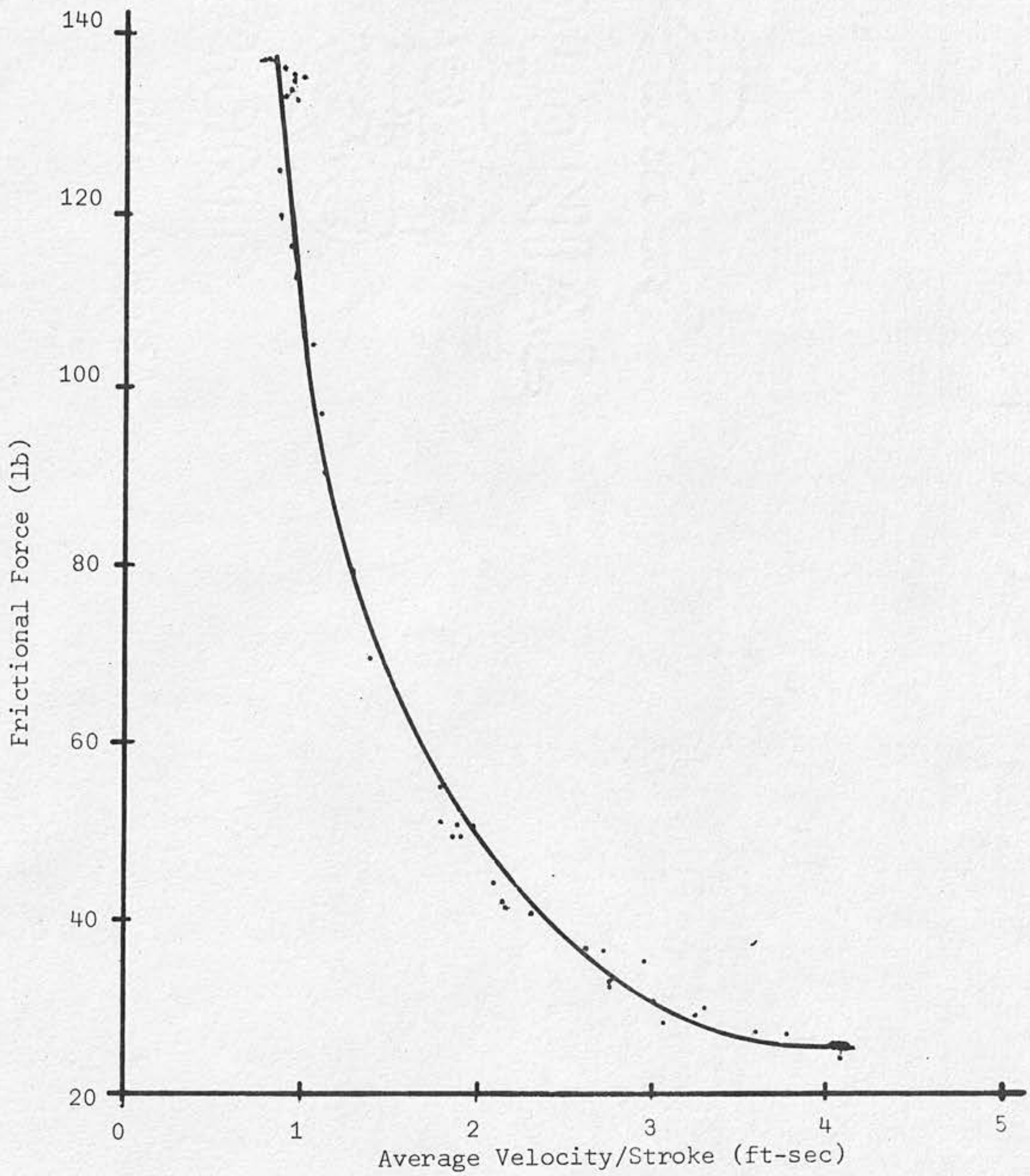


Figure 16 Frictional Force/Tool Velocity Relationship; nominal amplitude = 0.020 ft, tilted plane of oscillation with tension springs.

of the precautions taken, tightening of the spring in the clamp with a crank caused a momentary force which added to, or subtracted from, the frictional load sensed by the draught transducer. The average, however, was largely unaffected by this procedure. It is on this basis that drawing of a smooth curve through the middle of the points was justified.

Using the equations for t and A noted above, values were calculated from the indicated relationships of F and V. These were subsequently plotted and may be seen in Figure 17. An interesting observation is that the "load" torque was, in general, less than 1 ft-lb for the range of the frictional load applied.

An attempt was made to find a criterion for determining the "load" torque from the input torque recorded while tilling the soil. The input torque, which was obtained along with the velocity and friction load above, was plotted against the velocity. The velocity scale was converted to amplitude as for Figure 17. Unfortunately, the correlation was poor (see Figures 18 and 19) and it was impossible to estimate the amplitude for a specific value of the input torque. It was now necessary to abandon this approach as well. Though in some respects too much time was spent on the investigation, the observation that the amplitude was a function of the frequency was a very important clue. Before making use of this observation, it is necessary to note the following.

When one body slides on another;

$$F = \mu N$$

where F is the frictional force,

μ is the coefficient of kinetic friction, and

N is the normal pressure.

In the bearings of a slider-crank mechanism;

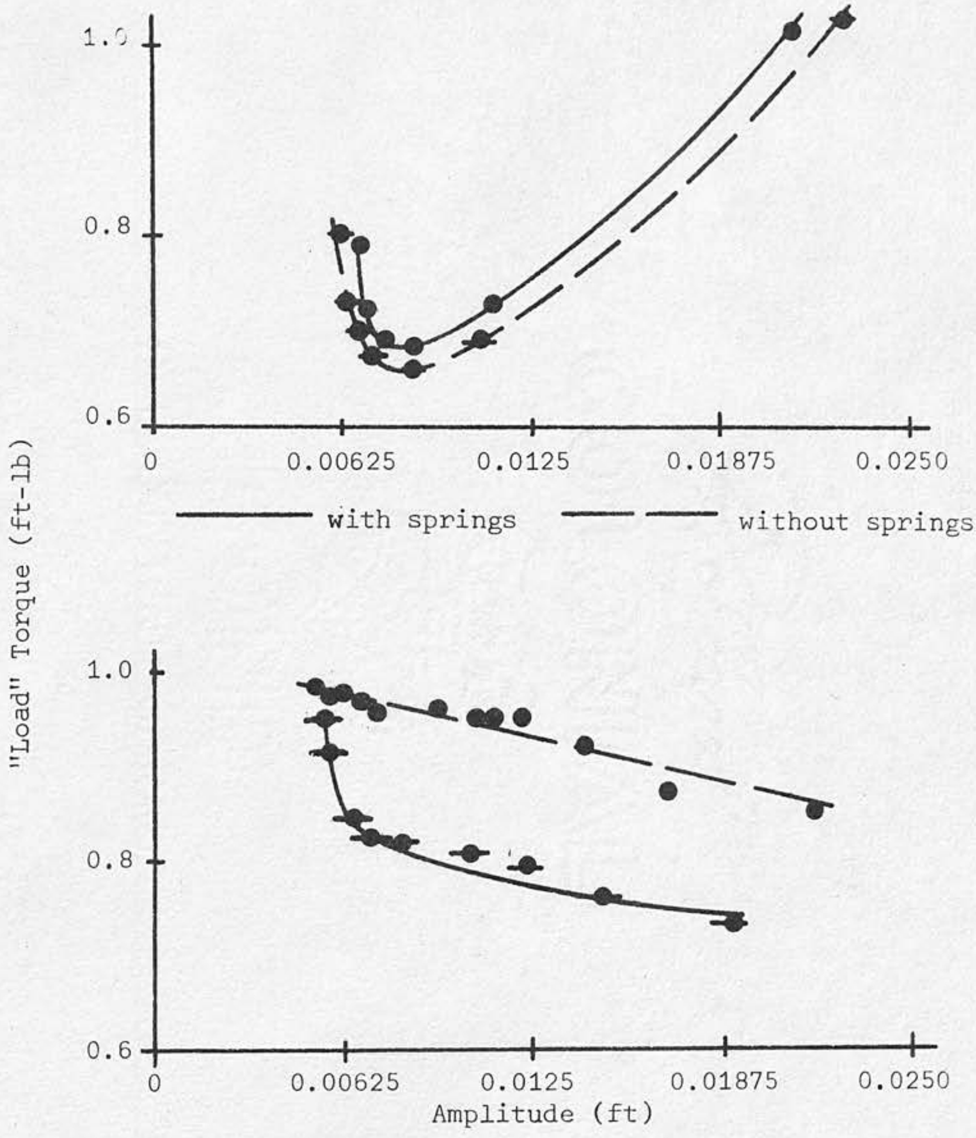


Figure 17 "Load" Torque/Amplitude Relationship; top - horizontal plane of oscillation, btm - tilted plane.

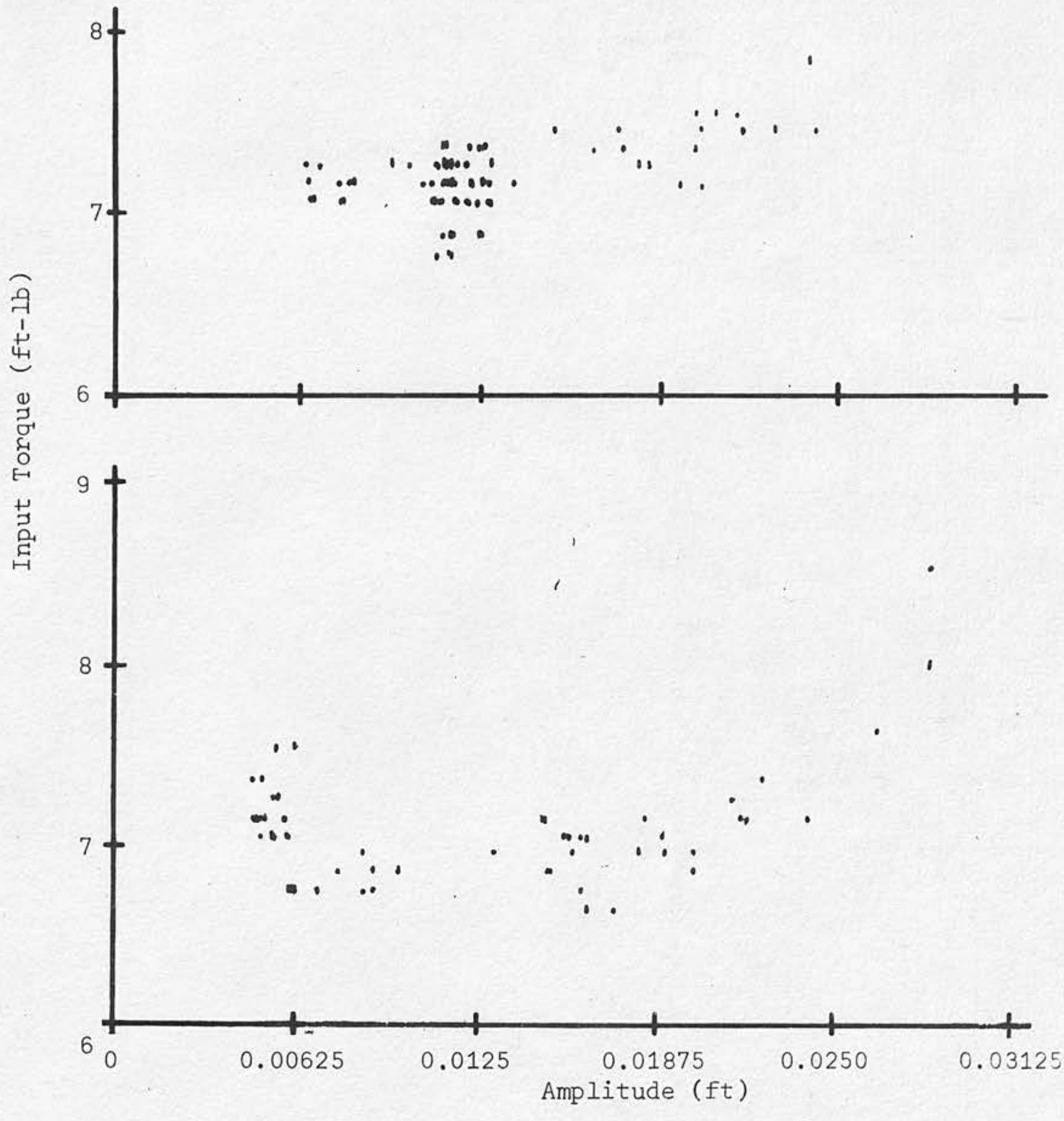


Figure 18 Input Torque/Amplitude Relationship; top - horizontal plane of oscillation, btm - tilted plane.

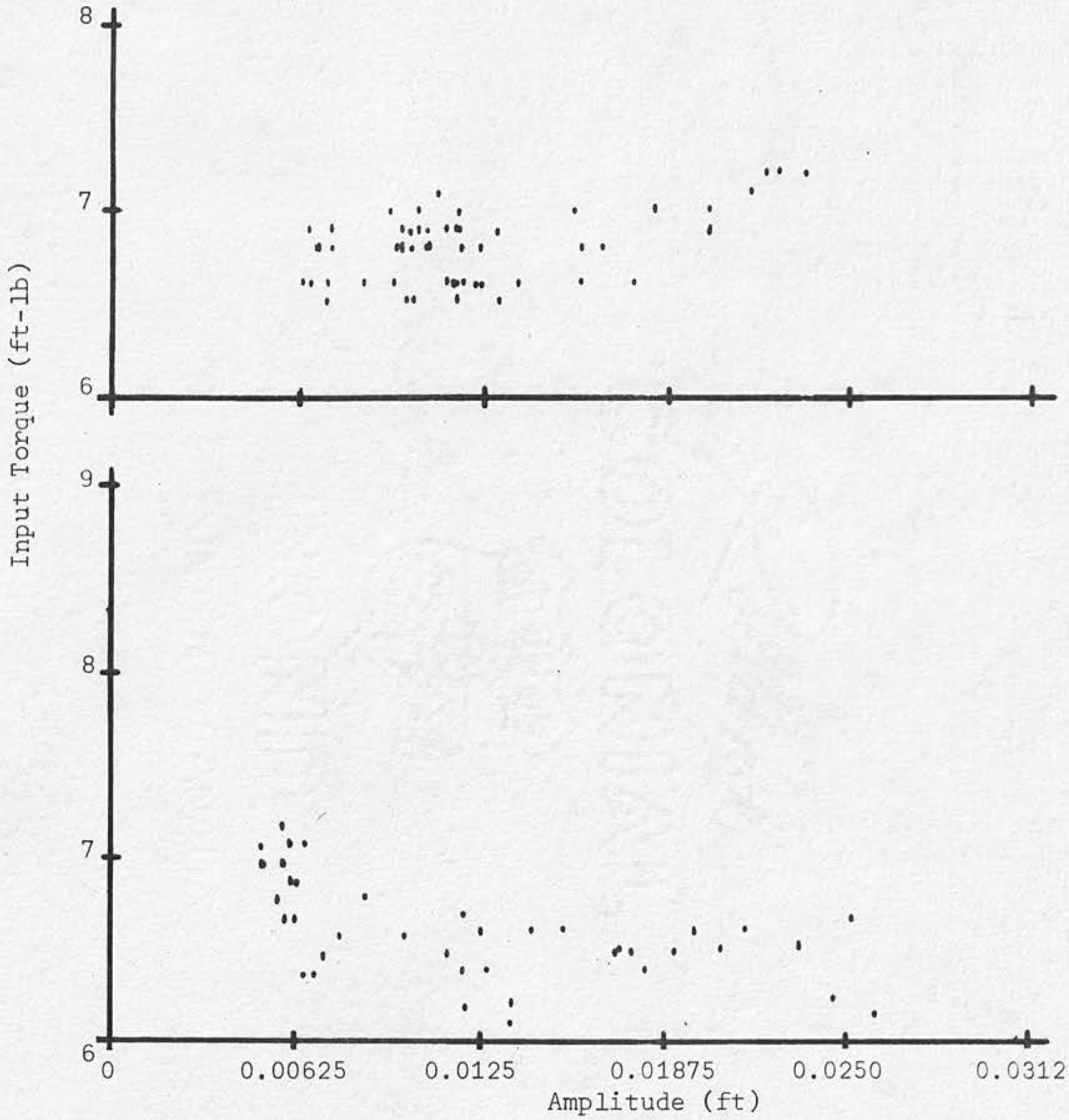


Figure 19 Input Torque/Amplitude Relationship with Tension Springs; top - horizontal plane of oscillation, btm - tilted plane.

$N = m\ddot{x}$

where m is the oscillating mass, and

$\ddot{x}$ is the acceleration in the plane of oscillation.

The acceleration of gravity would have to be considered if the plane of oscillation was tilted considerably and $\ddot{x}$ was small. From the above;

$F = \mu m\ddot{x}$

From Kells (51), the mean is given by;

$$v' = \int_a^b v\,du / \int_a^b du$$

or,
$$\ddot{x}' = \int_{T_0}^{T_1} \ddot{x}\,dT \Big/ \int_{T_0}^{T_1} dT$$

where T_0 to T_1 is a time interval.

From equation 10, chapter 8 and for a horizontal plane of oscillation;

$$\ddot{x} = -\omega^2 A\cos\delta$$

By substituting ωT for δ (see equation 4 chapter 8) in the above;

$$\ddot{x}' = \int_{T_0}^{T_1} -\omega^2 A\cos(\omega T)\,dT \Big/ \int_{T_0}^{T_1} dT$$

$$= \Big(-\omega A\sin(\omega T)\Big)_{T_0}^{T_1} / (T)_{T_0}$$

For a complete cycle, $\ddot{x}$ reverses direction and, therefore, $\ddot{x}'$ would be zero. For a half cycle from δ of $\pi/2$ to δ of $3\pi/2$, $\ddot{x}$ is in one direction only, and;

$\delta_0 = \omega T_0 = \pi/2$, and $\delta_1 = \omega T_1 = 3\pi/2$, or

$T_0 = \pi/2\omega$, and $T_1 = 3\pi/2\omega$, hence

$$\ddot{x}' = \Big(-\omega A(\sin 3\pi/2 - \sin \pi/2)\Big) / \Big((3\pi/2\omega) - (\pi/2\omega)\Big)$$

$$= \omega^2 A/\pi, \text{ or}$$

$$F' = \mu m\omega^2 A/\pi$$

where F' is the mean friction.

Because friction is always positive, F' is also the mean friction for δ of $3\pi/2$ to δ of $\pi/2$ and, therefore, for the complete cycle and succeeding cycles. Thus,

$$t' = kF'$$

where t' is the mean torque associated with F', and

k is a constant, or

$$t' = k\mu m\omega^2 A/\pi$$

$$= 4k\mu m\pi A f^2$$

where $f = \omega/2\pi$, then

$$t' = KAf^2$$

where $K = 4k\mu m\pi$

From the prior investigation it was apparent that;

$$t' \neq 0 \text{ when } f = 0, \text{ or}$$

$$t' = t_0 + KAf^2 \qquad -1$$

Also from the investigation, it was apparent that without a load on the tool;

$$A = A' + kf$$

where A' is the initial amplitude, or

$$t' = t_0 + KA'f^2 + kKf^3 \qquad -2$$

It follows that equation 2 is representative of the relationship between the "frictional" torque and the frequency for Figures 7 to 12 whereas equation 1 is representative of the relationship while tilling the soil if the amplitude was essentially constant*. That is, equation 1 can be used to estimate the "frictional" torque while tilling the soil if the assumption regarding the amplitude is valid and the coefficient K can be determined.

* The assumption is discussed with respect to the tool displacement in Chapter 8.

Determining K from equation 2 appeared to be formidable because of the procedure required to fit the "frictional" torque data in Figures 7 to 12 to a polynomial. To avoid this, the data was fitted to an exponential in the form of;

$$t = cb^{f} \qquad -3$$

using a method suggested by Steel and Torrie (87). The appropriateness of this relationship was revealed by the straight line obtained when the data was plotted on semi-logarithmic paper. The procedure, then, was to set the slope of the tangent of equation 1 equal to equation 3 and solve for KA. The procedure assumes that, for small values of f, k = 0. Equation 3 may be written;

$$\log t = \log c + f(\log b)$$

$$t = \log^{-1} (C + fB)$$

where $C = \log c$

$B = \log b$

The slope of the tangent for equation 3 is,

$$m = dt/df = cb^{f}B$$

$$= B \left(\log^{-1}(C + fB)\right) \qquad -4$$

The slope of the tangent for equation 1 is;

$$m = dt/df = 2KAf \qquad -5$$

Equating 4 and 5 and solving for KA,

$$KA = B\left(\log^{-1}(C + fB)\right)/2f \qquad -6$$

In determining KA it was necessary to avoid zero frequency because, at this level, the slope of the tangent to equation 1 is zero whereas it is not for equation 3. The choice of the frequency to be used is discussed in Chapter 9. The intercept with the torque axis from equation 3 (f is zero) is;

$$t_0 = \log^{-1}C$$

In determining the values of C and B, paired values of t and f were taken from the curve drawn through the data of Figures 7 to 12. The calculated values of C and B are given in Table 1.

Table 1 "Frictional" Torque/Frequency Relationship Constants.

Nominal Amplitude (ft)	0.010	0.020	0.012	0.018
Without Springs				
C	-0.81861	-0.73070	-1.02078	-0.88654
B	0.03326	0.04221	0.04694	0.05179
With Springs				
C	-0.70266	-0.65625		
B	0.02678	0.03778		

Tool Geometry

The dimensions and the orientation of the vertical and horizontal tools used are given in Figure 20. The vertical wedge may be seen in Plate 6. As the wedge was available prior to the start of the project, it was included, largely to explore the anticipated mechanical and soil preparation problems. Discussion and selection of the rake angles of the horizontal tools are noted in Chapter 8. In order for both tools to be geometrically similar, except for the rake angle, some dimensions were dictated by the physical limitations of the tool with no rake angle. The approach angle (37) for both horizontal tools was arbitrarily selected as an approximation of a worn tool. The necessity for altering the vertical location was to compensate for changes in the height when the vibratory frame was rotated to change the plane of oscillation.

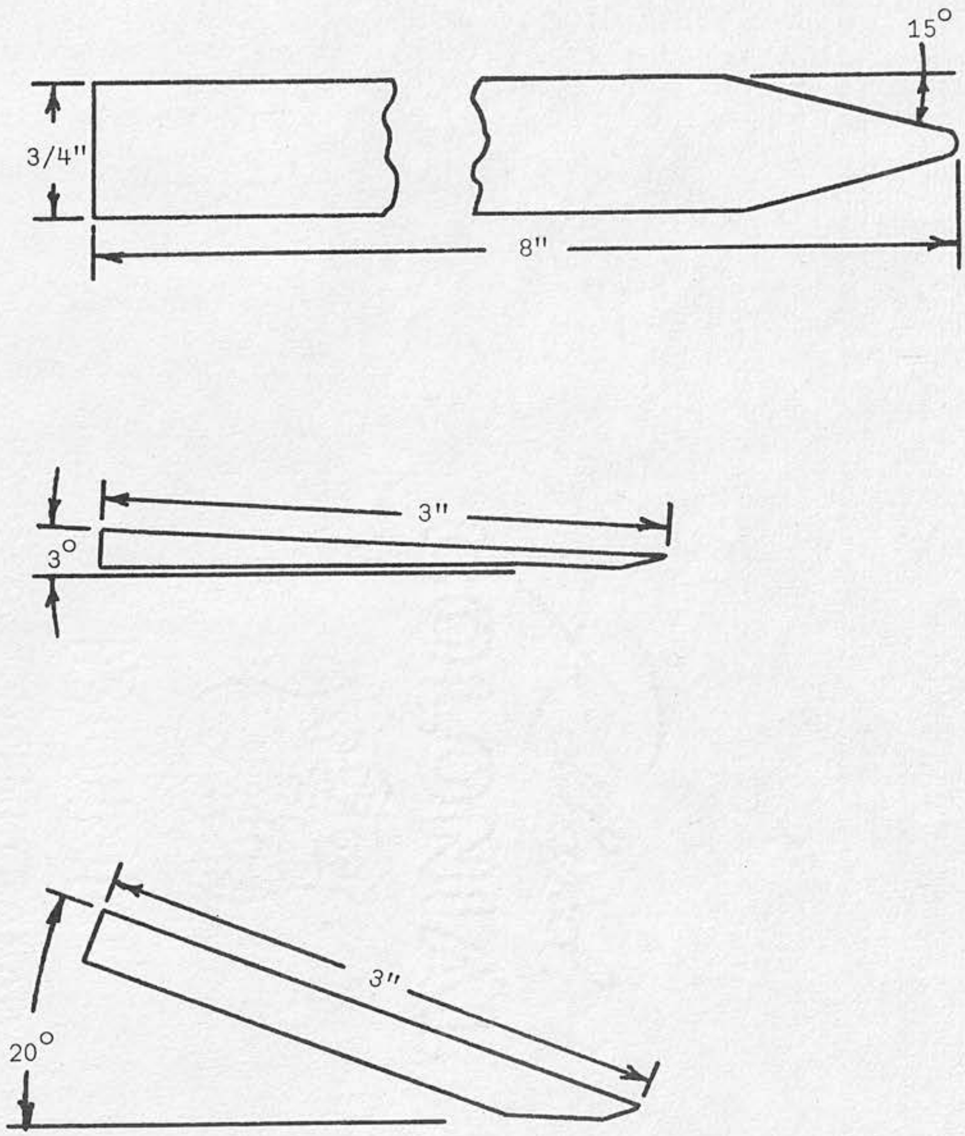


Figure 20 Tool Shape; top - vertical wedge, mid - horizontal with no rake angle, btm - horizontal with 20° rake angle.

Transducers

The sensing elements or transducers of the instrumentation measured the following:

- the speed or travel rate of the tillage cart,
- the force or draught required to maintain the cart velocity,
- the rotational speed of the crank shaft of the vibratory drive or the frequency of the tool oscillation, and
- the input torque to the crank shaft required to maintain the frequency.

The draught transducer may be seen in Plate 5 (btm) and the frequency and torque transducers in Plate 6 (right). The receiver of the torque transducer is the cylindrical object with a single electrical cable. The transmitter is also cylindrical in shape, but has a toggle switch and a receptacle for plugging in a battery charger. The frequency transducer is the object with two electrical cables. The travel rate or speed transducer may be seen in Plate 5 and is the "fifth-wheel" of the tillage cart. These transducers may also be noted in the schematic diagram of the instrumentation in Figure 21.

The draught and torque transducers were basically strain gauges bonded to suitable structural members. The gauges produced an electrical voltage which increased, in the former case, when the member elongated due to the pull, and, in the latter, when it twisted due to the torque. Additional details of both transducers have been noted by Blight and Carlow (11 and 12). For example, the voltage output of the strain gauges was taken to a modulator which consisted of a voltage controlled oscillator. In other words, the output or analogue signal of the transducer was an alternating voltage in which the frequency was proportional to the elongation or twist. In the case of the torque transducer, it provided an unique feature. As noted by the authors,

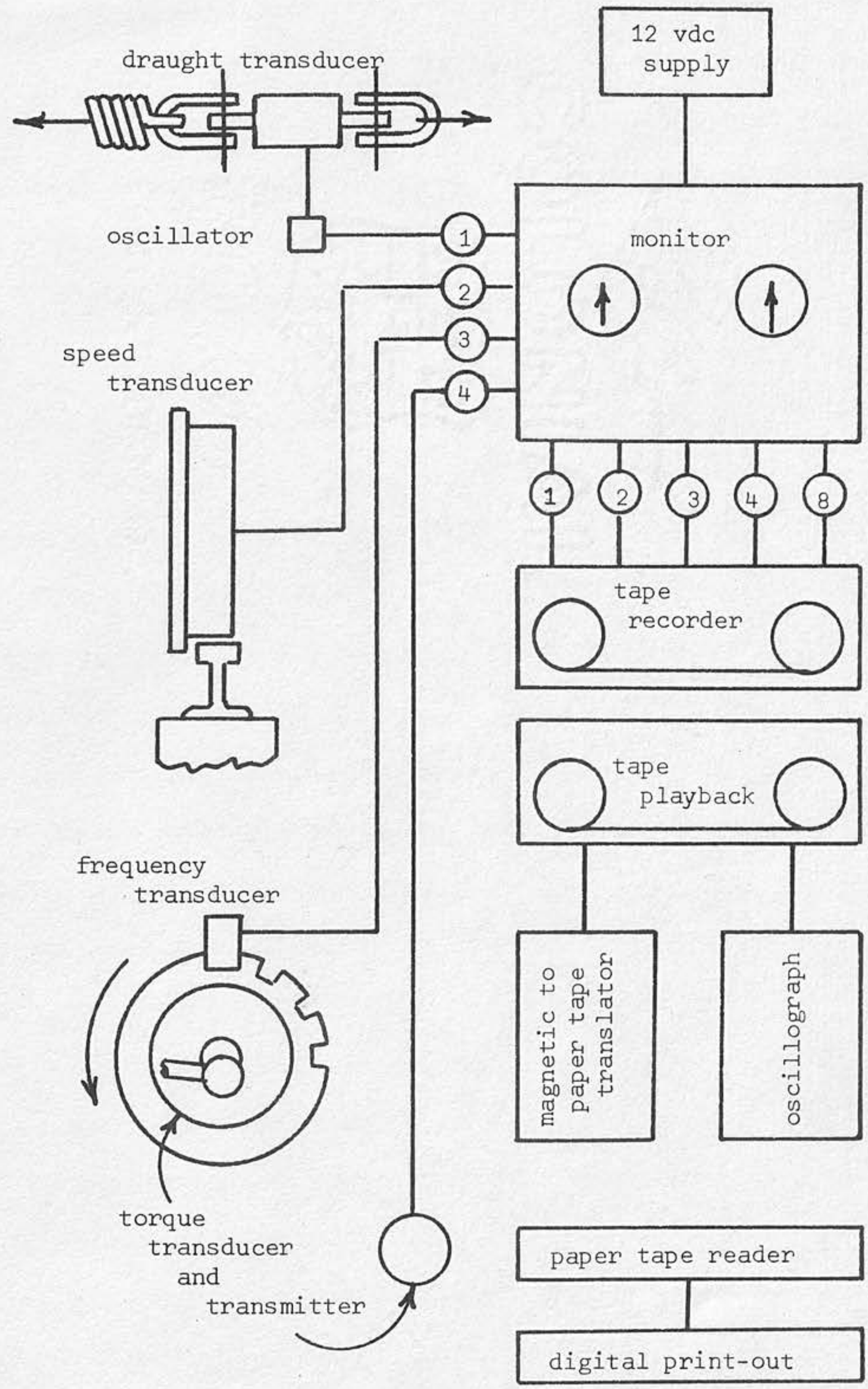


Figure 21 Schematic of the N.I.A.E. - S.S. Instrumentation.

it incorporated "....radio transmission of the signal from the torque meter to a remote receiver, obviating the need for slip-rings and brushes." Though the two transducers used were not those described by the authors, they were similar in design.

The frequency range of the two transducers was 3000 to 6000 cps (Hertz). The former is the base frequency which is obtained when there is "no load" or "zero strain" in the sensing element. The load (pull or torque) is calculated by multiplying the difference between the load and the base frequency by the appropriate calibration constant. One common problem with transducers is their tendency to "drift". That is, it is impossible to maintain a "zero electrical output" for "zero strain". In the case of the torque transducer, the "drift" in the base frequency was large and was not random with respect to time. To overcome this difficulty, the base frequency was determined immediately after recording the load frequency. Unfortunately, it was impossible to obtain "zero strain" in the vibratory drive. This contributed to the variation in the torque observations but the advantage was that the error was random. Other than reducing the precision of the experiment, the only other difficulty this procedure caused was in adjusting the torque values for friction in the vibratory drive.

The "drift" of the base frequency of the draught transducer was smaller and was random with respect to time. For simplification, the same procedure regarding the base frequency was used. By doing so, it was possible to partially compensate for the rolling resistance of the cart. The short chain, which prevented the draught transducer from dragging on the ground, imposed a small load which was nearly equal to the rolling resistance. That is, the base frequency used to calculate the draught was not equivalent to zero but approximated the rolling resistance of the cart.

Details of the speed transducer were given by Carlow (17). In essence, a rotating graticule, engraved at suitable intervals, interrupted a light beam falling on a phototransistor. The pulse repetition or frequency was proportional to the speed of rotation. For the frequency transducer, the graticule consisted of a notched disk which was attached to the crankshaft. The frequency was originally sensed by a commercial capacitor type transducer. This failed during the trials and may have been a victim of the vibration noted previously.

The calibration or output of the torque transducer for a given input was obtained which established that the relationship was linear. For this, the torque transducer was fixed and a two-foot arm attached to its shaft. Weights, of known values, were hung on the arm. The torque transducer was recalibrated when a zener diode, which controlled the voltage across the strain gauge bridge, faulted. The calibration of the speed transducer was obtained at the same time as the velocity of the tillage cart was set. The variable speed transmission in the winch drive was adjusted until the cart passed two markers in a specified time. The number of pulses per second of the transducer was equated to the calculated velocity. The calibration of the frequency transducer was evident from noting the number of notches in the disk. With regard to the draught transducer, it had been in use for some time at the Institute and so its calibration was accepted without further tests.

The vibration caused many faults in the instrumentation, especially during the first part of the experimental work. Breaking of soldered connections was the most common problem. The difficulties were compounded in the case of the receiver of the torque transducer. It malfunctioned only while being vibrated, behaving normally at other times. When this occurs it is virtually impossible to locate the source of the trouble and the best remedy is to try and isolate the component from the vibration. Plate 6 illustrates the complexity that this required. The plastic tube of the receiver was supported in a larger plastic tube by foam rubber. The plate, to which this larger tube was fastened, was mounted on the sub-frame of the cart through isolation springs. The mass of the receiver was augmented by the plate and several attempts were required at altering its weight before a satisfactory spring-mass system was obtained.

The springs which were used to attenuate the variation in the cart velocity were located between the cart and the draught transducer in order to isolate the latter. The platform, which carried the power supply, monitor, and tape recorder, was also isolated by a set of springs. Only two components could not be isolated in some manner and they were the transmitter of the torque transducer and the phototransistor of the frequency transducer.

Measurement of Soil Density

The levels of soil density obtained with the roller at different indices were measured by a technique which employed the behaviour of gamma-ray transmission through the soil. Details have yet to be published, but the basic principle was given by Soane (82). Essentially one probe of the pair (see Plate 8) contained a detector, (which has an attached electrical cable) and the other, a low activity gamma-ray source. The time required to obtain a given number of gamma-ray counts was indicated by the scaler-timer (box with dial). The time was inversely related to the wet density of the soil. This relationship was affected when the source-detector was close to the soil surface. In order to avoid this, it was the practice to place a wooden block between the probes. When this was found insufficient additional soil was dumped on the surface with the blade of the power unit.

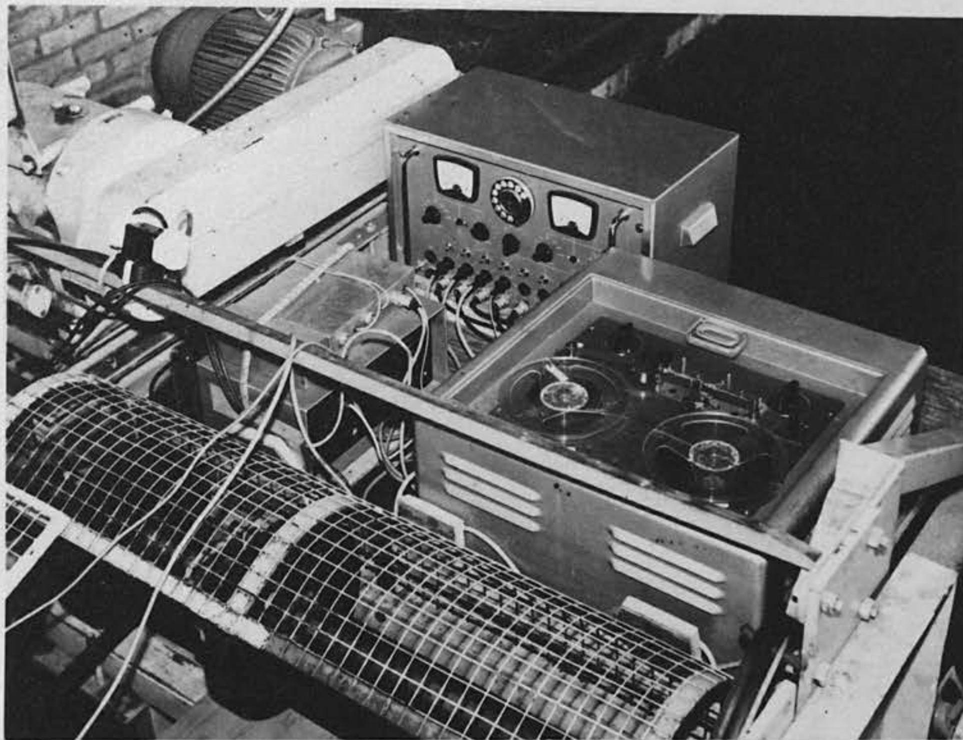


PLATE 8 TOP - MONITOR, POWER SUPPLY AND TAPE RECORDER FOR THE TRANSDUCERS
BTM - GAMMA-RAY TRANSMISSION EQUIPMENT FOR MEASUREMENT OF SOIL DENSITY

Holes for the probes were obtained by driving spikes through a jig into the soil. The spikes were removed and the probes were then pushed into the soil to the desired depth. The time required for the given number of counts was determined. The probe was then pushed a further 2 in. into the soil and another time-sample was obtained. The procedure was repeated until the maximum depth of interest was achieved. The whole procedure was then repeated for other sites in the soil tank. A mean of the time-samples was calculated, either for all the readings or for those at the same depth, depending on the particular need. The mean or means were converted to wet density with the use of a calibration chart. As noted in the next chapter, soil samples were taken to determine the soil moisture so that the dry density could be calculated.

Data Logging

The relationship of the four transducers to the other components of the instrumentation used may be seen in the schematic diagram of Figure 21 and partially illustrated in Plate 8 (top). The monitor acts as a link between the transducers and a magnetic tape recorder. The monitor had two galvanometers which provided direct indication of the transducer analogue signal. These informed the operator that the transducers were functioning, but were not used for recording purposes. Though the two meters could be switched to any one of the "channels", it was not practical to observe more than two transducers for runs of short duration. This meant that a malfunction in the other two transducers was not detected until the tape was "played back" sometime later; that is, instead of losing the occasional observation, many were lost and the whole replicate had to be repeated.

Another function of the monitor was the provision of timing pulses (see below). These pulses were recorded on the magnetic tape along with the other data. Details of the recorder are provided by Carlow (16). Essentially, it was an eight-channel recorder with suitable tape drive, recording head, and amplifiers with a trigger output to give a sharply defined pulse.

The magnetic to paper tape translator converted the analogue frequency signal into digital form. The operation of the translator has been described by Dr. D.P. Blight of the N.I.A.E. - S.S. in an unpublished paper. The relevant paragraph is;

"The pulses recorded on each of the appropriate tape channels are stored, and, on receipt of a print-out command are punched sequentially on paper tape, using a Teletype tape punch. The period of time over which the count accumulates can be selected within the range 1/3 - 3 sec in steps of 1/3 sec obtained from the 3 kc/sec master oscillator in the monitor unit. The equipment, therefore, operates in real time, and the playback speed of the magnetic tape does not affect the validity of the results."

Later, in this same paper the author has written, "The punched paper tape can now be fed into the computer. If it is felt to be desirable to examine the numerical values obtained before processing, the tape can be read into the tape editing desk to obtain a page print-out of the data."

One final piece of equipment requires comment. The analogue signals of the transducers recorded on the magnetic tape could be visually examined by means of an ultra-violet oscillograph. This proved to be most useful as momentary faults were easily detected and which would have been missed except in a most thorough examination of the digital print-out.

An illustration of draught and travel rate is given in Figure 22.

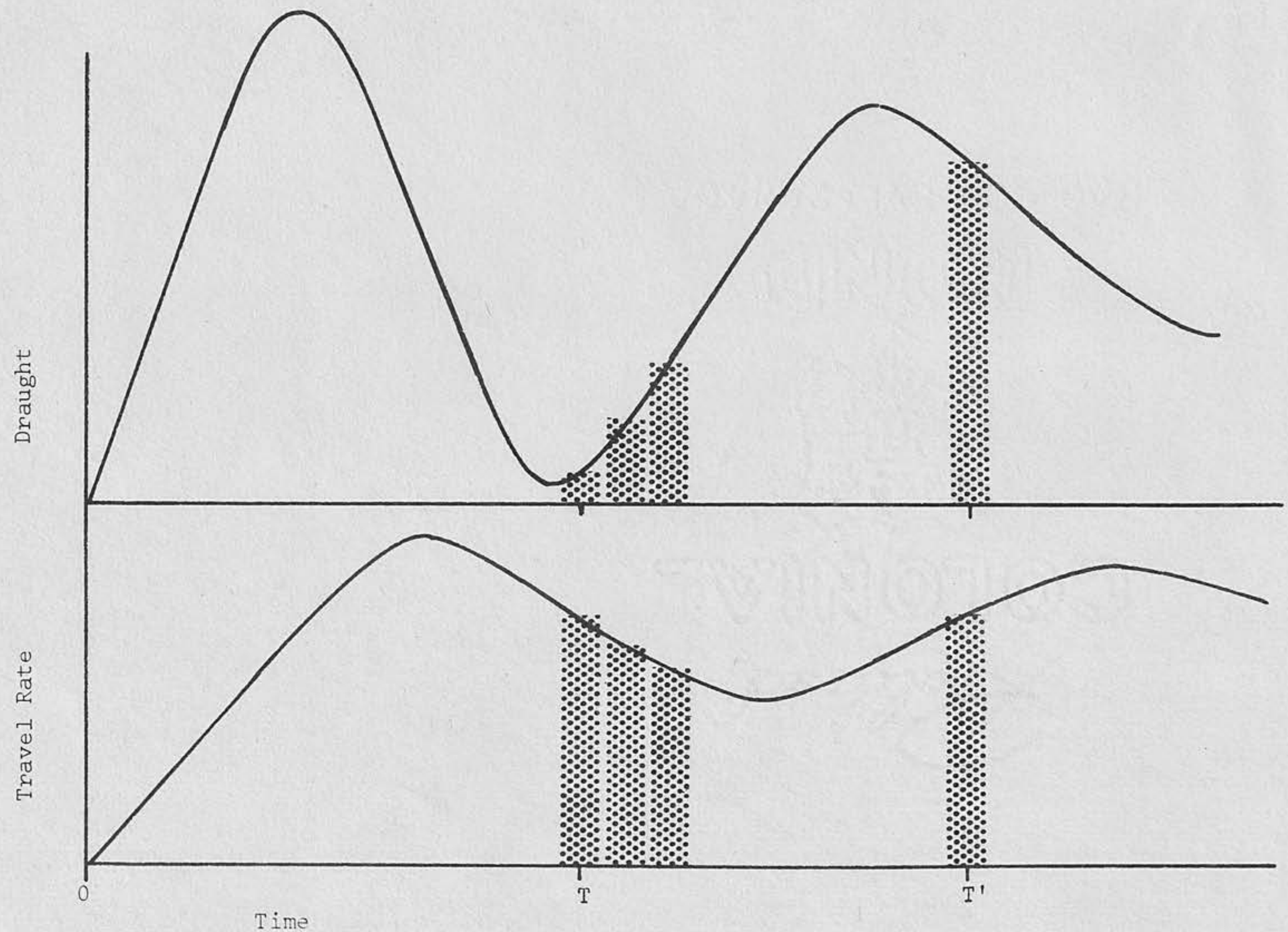


Figure 22 Instantaneous and Integrated Values of Draught and Travel Rate.

The solid lines represent the instantaneous values as recorded by the oscillograph. The accumulations or integrated values (only a few are shown) are represented by the vertical bars with their scaled height equalling the count of the pulses for the time interval of integration. The minimum time interval was used throughout the experimental work.

Data Processing and Analysis

Using a computer programme developed by Dr. D.P. Blight of N.I.A.E. - S.S., the base frequency was subtracted from the load frequency and the difference multiplied by the appropriate calibration constant for the draught and torque transducer. For the speed and frequency transducer there was no base frequency and, therefore, this step was not required. In addition, the programme provided for the calculation of the drawbar, shaft and total horsepower and the mean of these values as well as for the draught, torque, frequency and travel rate. The calculation for the horsepower was as follows:

$$DHP = \text{draught} \times \text{travel rate}/550$$

$$SHP = 2\pi(\text{torque} \times \text{frequency})/550, \text{ and}$$

$$THP = DHP + SHP$$

where DHP is the drawbar horsepower,

SHP is the shaft horsepower, and

THP is the total horsepower.

In order to determine the means, it was necessary to specify which 1/3 sec accumulations were to be included. This was complicated because the mass of the cart was large; that is,

$$\text{transducer pull} = \text{draught} + m\ddot{x}$$

where $\ddot{x}$ is the acceleration and which may be positive or negative. The mean of $m\ddot{x}$ is zero, however, if the travel rate at the end of the last accumulation is equal to the travel rate at the beginning of the first. That is,

$$m\int_{v}^{v'} \dot{x}dv \; / \int_{v}^{v'} dv = 0$$

if v is equal to v'. Under these circumstances;

$$d = (\Delta p_1 + \Delta p_2 + \quad + \Delta p_x)/x$$

where d is the mean draught,

x is the number of 1/3 sec accumulations, and

$$\Delta p_1 = \int_{T_0}^{T_1} dp/dT \; / \int_{T_0}^{T_1} dT$$

and where dp/dT is the instantaneous rate of change in the pull.

Except when dv/dT and dv'/dT are both zero or opposite (slopes of the tangent are zero or opposite), v will not equal v' when Δv_1 is equal to Δv_x, where,

$$\Delta v_1 = \int_{T_0}^{T_1} dv/dT \; / \int_{T_0}^{T_1} dT$$

It was rare that all of these conditions could be satisfied within the imposed limits of travel. It was evident, however, that v could equal v' when Δv_1 was greater than Δv_x, if dv/dT and dv'/dT were both positive or increasing, and when Δv_1 was less than Δv_x, if dv/dT and dv'/dT were both negative. The criteria for selecting the appropriate accumulations may be seem more readily by referring to Figure 22. The vertical bar of the travel rate (Δv_1) at time T is the same height as at time T'. Because the slope at T and at T' are opposite, the travel rate at the beginning of the first accumulation is equal, or nearly equal, to the travel rate at the end of the last; that is, v is equal to v'. If the first accumulation occurred during the increase from zero, the slope would be of the same sign at T'. It can be seen that in order for v to be equal to v', Δv_1 would have to be larger than Δv_x.

The series of accumulations that best satisfied the conditions outlined above, and another series when the cart and the vibratory drive were stationary, were specified on a duplicate paper tape of all the accumulations. Prior to processing the data, it was necessary to transfer it onto a magnetic tape. The procedure of selecting and transferring resulted in a serious delay in obtaining the results from the computer.

The statistical analysis was largely carried out under the guidance of Dr. R.M. Cormack, Department of Statistics, University of Edinburgh, using at times statistical computer programmes of the Agricultural Research Council Unit. A statistical analysis of the soil densities was conducted using a programme of Dr. L. Baker, University of Alberta and of the Olivetti Underwood Ltd., for a desk-type or mini-computer. A statistical analysis "package" in APL at the University of Alberta was also used for the draught and total horsepower data obtained in the first part of the experimental work. Programmes for the mini-computer were developed for calculating sources of variation and regression coefficients, adjusting the torque for friction in the vibratory drive, plus a number of minor programmes for such calculations as the mean of the frequencies by soil and density.

CHAPTER 7

SOIL TESTS AND PROPERTIES

Soil Selection

The two soils used in experimental work were selected using the following criteria. They were to be:

- agricultural soils taken from the cultivated horizon of important crop-producing areas of Scotland,
- of different texture and colour, and
- within a reasonable distance of the Institute.

The reason for the colour difference was a visual indication if one soil started to mix with the other. Though the soils were to be located in opposite ends of the soil tank, mixing at the centre was a hazard.

One complicating factor in the selection was that few farmers were willing to part with the required 15 tons of valuable top soil. Originally, it had been hoped that one of the soils could be from the Biel Association because of its high clay content, but none of the farmers contacted were agreeable. The best compromise under the circumstances was a soil from the Hobkirk Series. The other soil selected was from the Dreghorn Series which provided the required difference in texture and colour.

According to Ragg and Futty (68), the parent material of the Hobkirk Series is a red sandstone which gives it a distinctive reddish colour. In the Munsell notation the hue, when the soil is dry, is 2.5 YR 3/4. The parent material of the Dreghorn Series is raised beach deposits. The high organic matter content gives it a brown colour which changed to black when wetted. In the Munsell notation the hue, when this soil is dry, is 10 YR 4/3.

Soil Index Properties

After the soils were delivered to the soil tank site, they were passed through a soil shredder. The red soil (Hobkirk) was subsequently sieved to remove stones. The sieve or riddle openings were 5/16" by 9 1/2". There were so few stones in the brown soil (Dreghorn) that sieving was considered unnecessary. The soil shredder and sieve used may be seen in Plate 9.

The Atterberg limits and the particle size distribution were determined by Mr. D.J. Campbell of the N.I.A.E. - S.S. using procedures adopted by the Institute (83). The brown soil is non-plastic. The properties of the red soil are as follows:

liquid limit - 25.8

plastic limit - 19.1

plasticity index - 6.8

The particle size distribution for both soils is given in Figure 23. They do not differ greatly one from the other. On the basis of the U.S. Department of Agriculture Texture Classification the red soil is a loam whereas the brown is a sandy loam.

Soil pF

It was noted in the literature review that soil strength is a function of the dry density and moisture content, and, therefore, both should be of interest in any tillage experiment. In order to compare results, it can be argued that when such experiments are conducted in two or more texturally different soils, they should have the same moisture content. A more convincing argument can be advanced that the soils should have the same pF. This follows for the observation that the pF of different textured

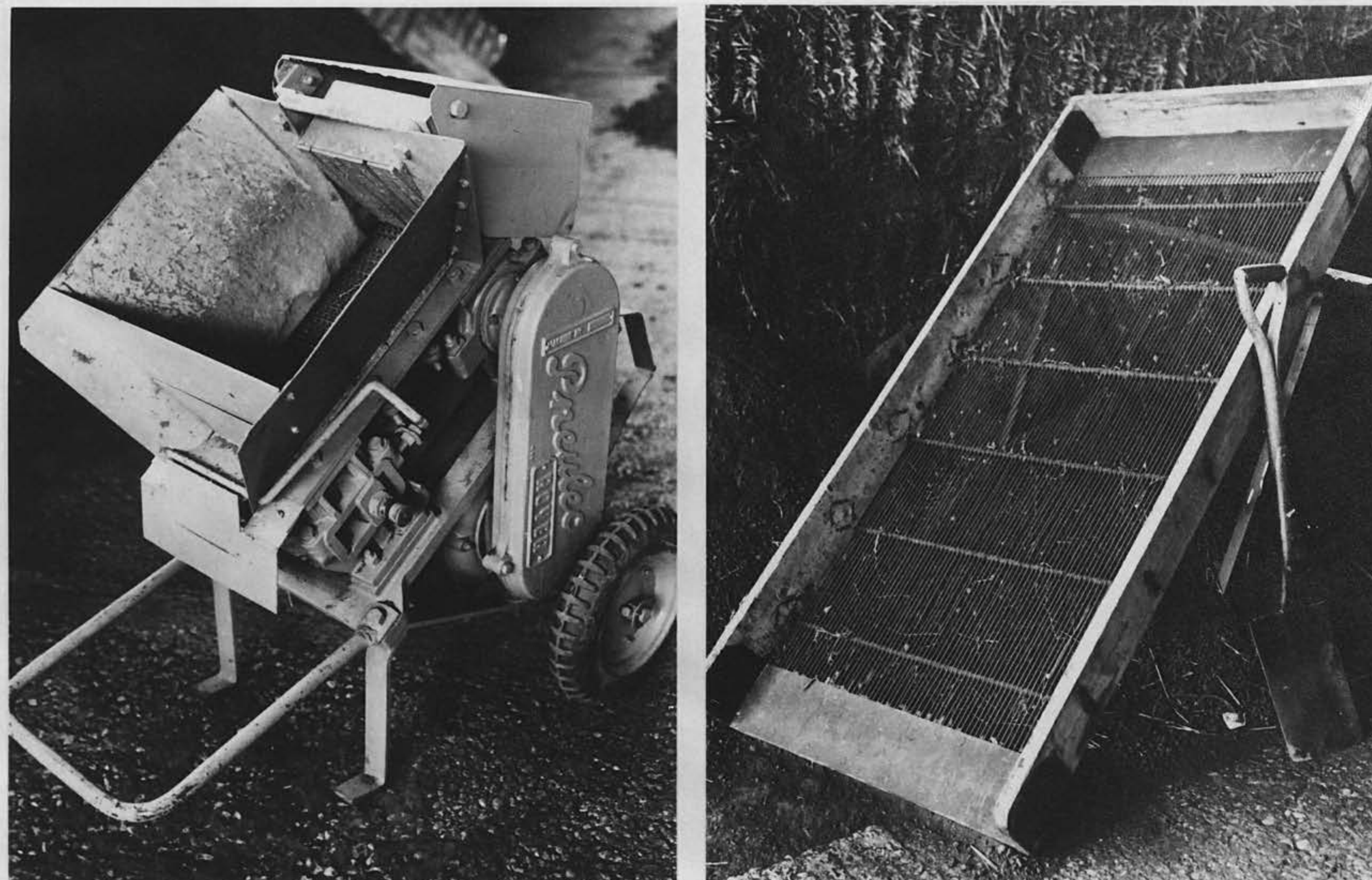


PLATE 9 SOIL CONDITIONING EQUIPMENT; LEFT - SOIL SHREDDER, RIGHT - SIEVE OR RIDDLE

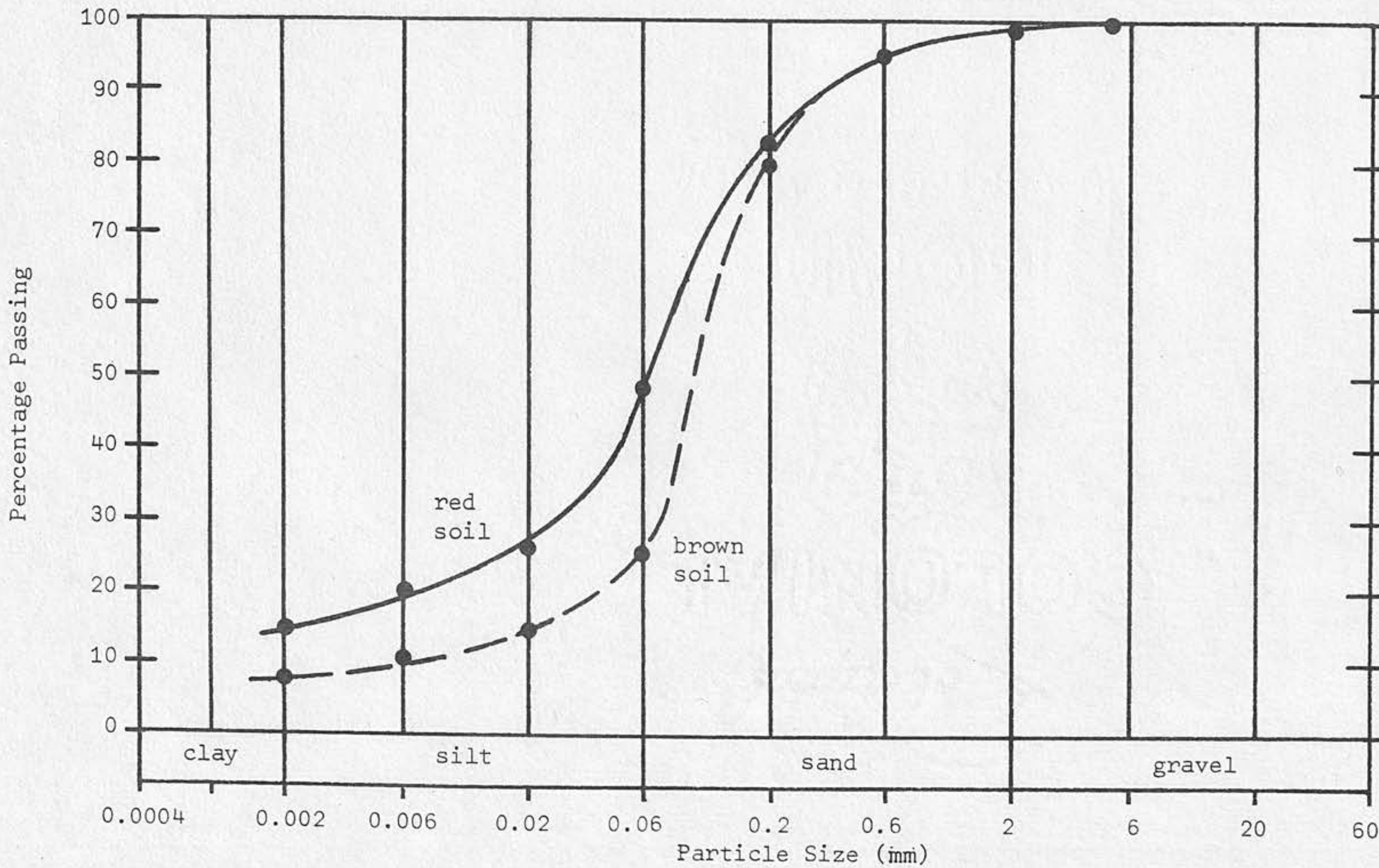


Figure 23 Particle Size Distribution of the Red and Brown Soils.

soils will be the same if they are subjected to similar climatic conditions. In view of this, the relationship of the moisture content and the pF were determined for the two soils.

Two methods were used for this, one being to subject the saturated soil samples to varying degrees of suction or pressure head. The tests were carried out by Mr. D.J. Campbell, again using procedures (83) adopted by the Institute. The soil was compacted into tubes which had a nylon mesh covering one end. The mean density for the red soil was 93.6 lb/cu. ft and for the brown 86.1 lb/cu. ft. The samples were then set into a tray of water in which kaolin had been allowed to settle. The kaolin provided a seal around the bottom of the soil sample and was in turn supported by filter paper. A small pipe below the filter paper was attached to a manometer which was lowered until a desired suction or negative head was obtained. For a pF of three, a positive head of one atmosphere of air pressure was applied instead to force the water out of the sample.

For higher pF values a technique employing the hygroscopic characteristics of conventional filter paper was used. This technique and the relationship of the pF and the moisture content of the filter paper is given by Fawcett and Collis-George (31). The moisture content of the soil and the filter paper was determined, as for all measurements of moisture content, on a dry basis. The soil samples and the filter papers were dried for eight hours in an oven with a temperature of 130°C. The sample size of the soil (as for all tests of soil moisture) was between 200 and 300 g.

The results of the pF tests are given in Figure 24. One difficulty with the filter paper technique was the loss of moisture after removal from the soil and before it was weighed. Though the paper was weighed as soon as

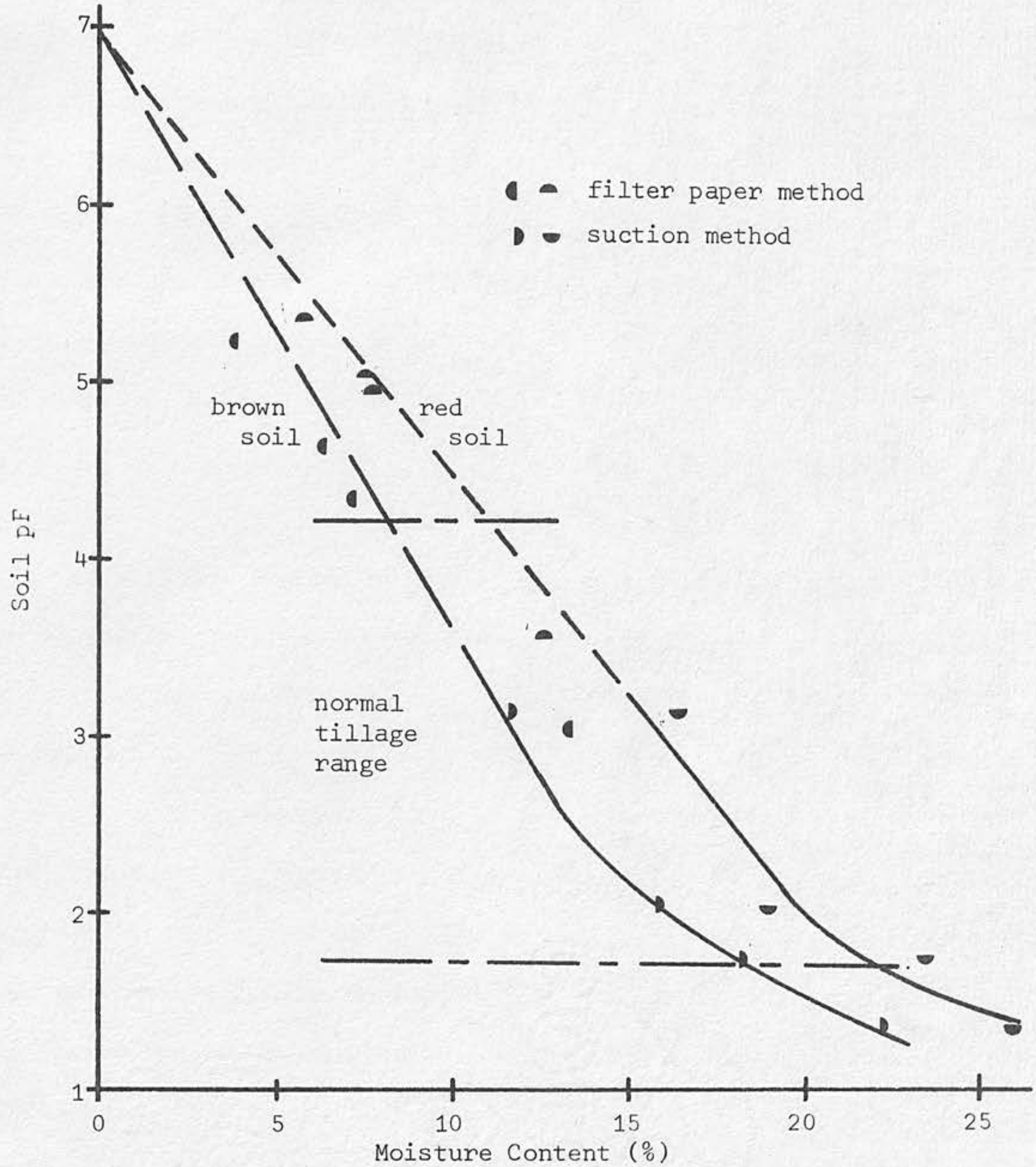


Figure 24 Moisture Content/pF Relationships of the Red and Brown Soils.

possible, it was necessary to take some time to brush off any soil that might be adhering to it. In view of this, the benefit of the doubt in fitting a curve was given to the values obtained by the direct method.

Tillage is usually carried out within the pF range of 2.7 to 4.2. According to Lyon and Buckman (61), a pF of 2.7 is equivalent to "field capacity" and seldom is tillage attempted when the soil is wetter than this. As for the other end of the range, it corresponds to the "wilting point" and this occurs infrequently except in arid and semi-arid areas. The moisture content difference, between the two soils for this range of pF, is 3 to 4 percent.

Moisture Content

The moisture content of the brown soil on receipt was approximately 16% which corresponds to a pF of less than 2. Drying of the soil was required in order to increase the pF to 2.7 or more. As the season was late, drying with unheated air was not feasible. A small paraffin or kerosene heater, a type frequently used on construction sites, was therefore secured. A plenum of a canvas tarpaulin and a polyethelene sheet was set up over the soil which had been placed in a ridge along the apron of the soil tank. The shape of the plenum was an inverted V which corresponded to the soil profile. The hot air, which was forced out of the combustion chamber by the integral fan of the heater, entered one end of the plenum and escaped along the bottom edges and the opposite end. As the surface soil dried, it was raked into the soil tank. It was a lengthy procedure, taking three weeks to reduce the moisture content of the soil by 5%. It was also inefficient in terms of the amount of water evaporated for the amount of fuel used. The practical considerations of time and expense dictated that reducing the moisture content of the brown soil below 11% was not practical. The pF for this moisture content was 3.2.

The moisture content of the red soil as received from the field was approximately 11%. Though this was equal to the moisture content of the brown soil after drying, the pF was much higher. To bring the two soils to the same pF, it was necessary to increase the moisture content of the red soil to 15%. The amount of water required was determined from the following:

$$W = mW_d$$

where W is the amount of water to be added,

W_d is the weight of the soil - oven dry basis, and

m is the desired change in the moisture content ratio.

To determine W_d, the soil was placed in the tank and compacted. The wet density of the soil was determined using the gamma-ray transmission equipment. To calculate the dry density, soil samples were taken to determine the moisture content. W_d was then estimated by multiplying the dry density by the volume of the tank occupied by the soil. The amount of water required to raise the moisture content of the red soil by 4% was approximately 60 gallons.

As the spraying system of the power unit was not available at the time, a tractor-mounted field sprayer was obtained. The important feature was the means to measure the amount of water being applied. The procedure followed was to spray the soil surface using about ten gallons of water. This was allowed to soak in and then about two inches of the soil was excavated with the back-hoe. The soil that remained in the tank was then levelled and the procedure repeated. Only about two-thirds of the water calculated above was applied. After the final excavation, the tank was refilled and the moisture content determined again. The remaining one-third of the water was then applied using the same procedures as before. The need to approach the desired moisture content in two steps was to avoid the risk of over-wetting. It also assisted in obtaining a uniform moisture content.

Compaction Tests

As a guide for arranging appropriate procedures for the roller, the relationship of the dry density and the moisture content for different levels of compaction was required. For this, the Proctor Tests were considered appropriate. In essence, the tests consisted of compacting the soil of different moisture contents into moulds with a hammer. The weight of the hammer, the diameter of its face, the height of its free fall and the number of blows are all specified along with the size of the mould. Details are given by many authors in civil engineering such as MacLean et al. (62). The common Proctor Test is defined by the American Association of State Highway Officials (A.A.S.H.O.), Test Designation T. 99-38, or the British Standard Compaction Test. A greater amount of compaction is provided for in the modified A.A.S.H.O. Compaction Test. A heavier hammer and a greater height of free fall is used which results in almost three times the compacting energy as the standard. Because lower densities than those achieved with either of these tests were required, a third test was devised. In it the height of free fall was 1/2 of that for the standard test. For convenience these tests are referred to as the modified, standard and special tests and are listed in the order of decreasing amount of compaction. The results for these tests for the two soils are given in Figure 25.

There is a correlation between the density and the amount of compaction except at the higher moisture contents. The lack of a relationship at the higher moisture occurred because the soils were approaching a saturated or zero air void condition. The moisture content at the maximum density for

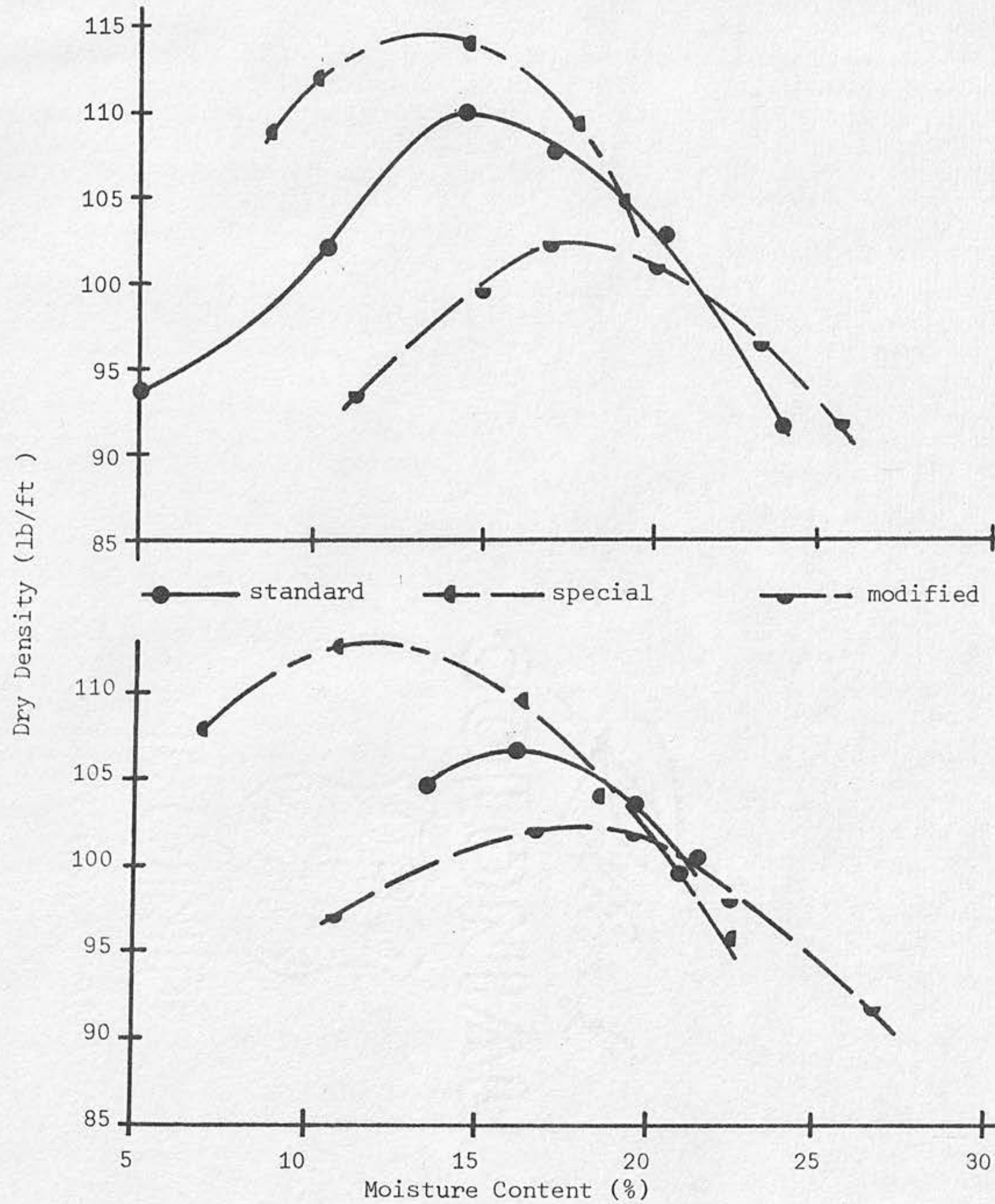


Figure 25 Moisture Content/Compaction Relationships;

top - red soil, btm - brown soil.

any level of compacting effort is referred to as the optimum moisture content. The optimum increased with a decrease in the amount of compaction. For the special test, it was approximately 18% for both soils. This moisture content was greater than that for normal tillage and was an indication that obtaining dense soil at a suitable moisture content would be difficult.

Soil Tank Compaction Trials

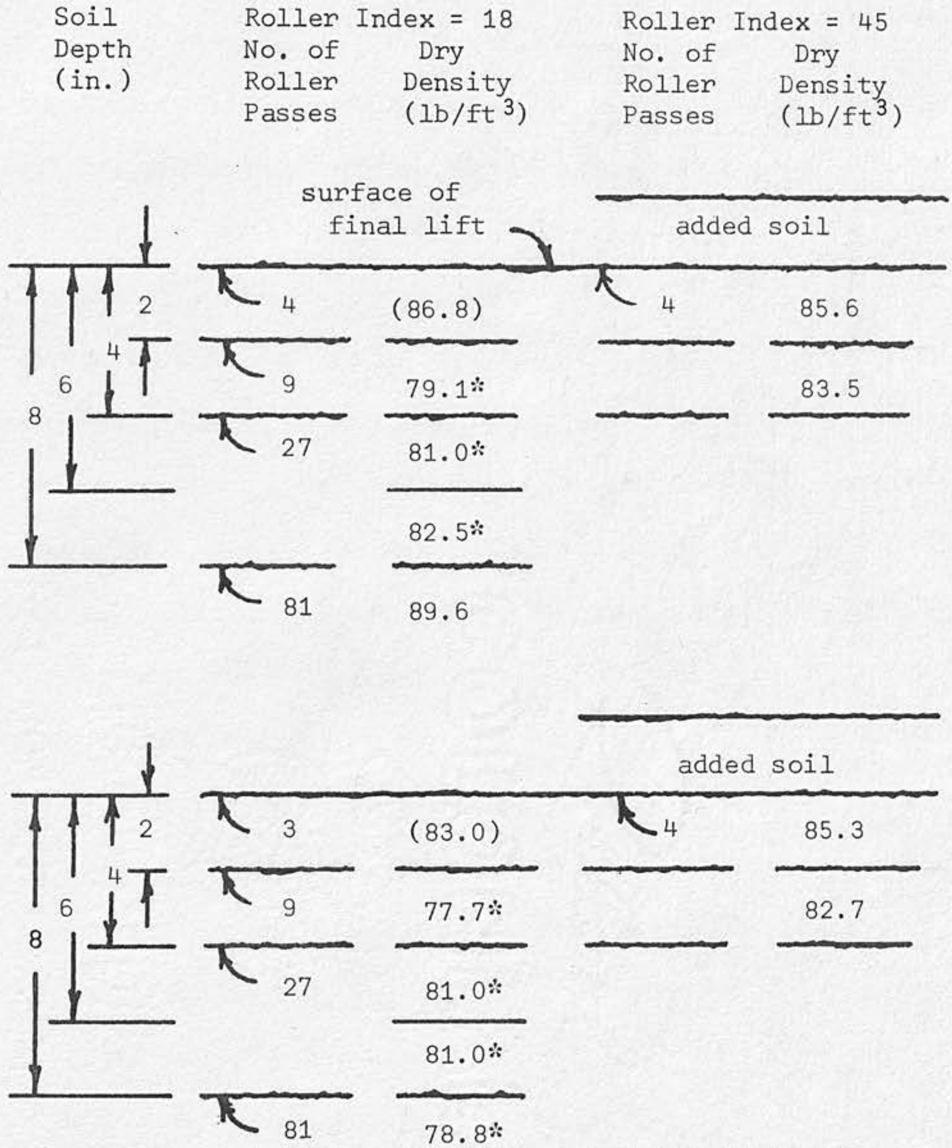
Roller indices of 142 and 311 lb/in. were noted by Lewis (48) for two road construction packers. The maximum dry densities he obtained with them were respectively 112 and 116 lb/ft^3. This was for compacting a sandy clay at its optimum moisture content. The index of the soil tank roller on the other hand was 18 lb/in. As the sandy clay used by Lewis was similar to the red and brown soils, it was clearly evident that dense soil could not be obtained with the soil tank roller unless it could be modified drastically.

The dry density according to MacLean et al. (62) is a non-linear function of the number of passes of the roller over the soil surface. For rollers similar to those noted by Lewis, they wrote: "The curves are characterized by a rapid increase in density for the first eight passes of both rollers followed in the case of the 2-3/4 ton roller by a slower subsequent increase in density. The gradual increase in density obtained after eight passes of the 2-3/4 ton roller is considered to be due to the decrease in the contact area between the rollers and ground, as the soil becomes firmer causing an increased pressure on the soil."

As a further complication, MacLean et al. (62) declare that a density profile, which diminishes with depth, is produced when the soil surface is rolled. It follows from this that the density gradient is minimized and a higher average density is obtained if only a portion of the soil is placed in the tank and rolled at one time. The sequence can then be repeated until a total depth required is obtained. Using this sequence the average density of the compacted soil depends on the number of increments or lifts of soil used in filling the tank. It was obvious from this, and prior observations and comments, that a compaction trial with the two soils at the desired moisture contents was required before appropriate compacting procedures could be specified.

For the trial, the tank was excavated to within four inches of the bottom. The soil remaining was levelled and then rolled 81 times. The roller index for this and subsequent lifts was 18 lb/in. Slightly more than four inches of loose soil was placed in the tank, levelled, and then rolled 27 times. The next lift was slightly more than two inches and was rolled nine times. The next lift was the same as the last and was rolled three times for the brown soil and was to be the same for the red but inadvertently one extra pass was made.

The soil density was determined using the gamma-ray transmission equipment. For these measurements twelve sites or replicates were used for each soil. At each site the soil density was determined at two-inch intervals of depth, so that the two-inch lifts were sampled once and the four-inch lift twice. The number of sites for the final lift was reduced from twelve to six. The original measurements for this lift were influenced by the proximity of the soil surface even though a greater depth was to have been simulated by placing a block of wood between the probes on the soil surface. This error was later confirmed by placing additional soil on top of the final lift and taking six additional measurements for this lift. The average dry density for every two in. of depth is given in Figure 26. If the mean of the final lift is ignored, because of the proximity of the soil surface, the statistical analysis indicates



* means not significantly different at the 5% level
( ) means omitted because of proximity of soil surface

Figure 26 Soil Tank Compaction Trials; Number of Passes/Density Relationships.

that only the treatment of 81 passes for the red soil was significant from the others (see Table 2 and Figure 26). In view of these results some alternative means to secure an appreciable greater density level was needed. Using a lift of less than two inches was not practical, and besides, the results of the four-inch lift eliminated it as a realistic possibility. There was no significant difference between the four and two-in. lifts. The only reasonable alternative was to increase the roller index.

The roller index was increased to 45 and the final lift of the previously compacted soil was rolled an additional four times. The results were somewhat disappointing as the gain in density was small. On the other hand, it is quite apparent from probing the soil that it was considerably firmer than when the index was 18 lb/in. This suggests that unless the soil density can be estimated with considerable precision it may not be a suitable parameter for defining the soil condition for tillage. That is, the soil firmness appears to change substantially for a small change in density.

In view of the results obtained, the roller index was increased from 45 to 60. The latter was the maximum possible with available equipment. Additional compaction trails were conducted at this index and also at 18 with regard to the number of passes. For each trial the planned tillage depth of 4 inches was excavated. The remaining soil was levelled and then rolled. The excavated soil was then placed back in the tank in two lifts with each lift receiving the same number of passes. The density was then determined for 15 sites, five across the tank and three down (See Appendix Table 7-8). This work culminated in specific compaction procedures which may be noted in Table 3 along with the mean of the soil density obtained. The statistical analysis (see Table 4) indicated that there was no significant difference

Table 2. Soil Density (time for 10,000 counts)/ No. of Roller Passes Relationship, Roller Index = 18 - Statistical Analysis[1]

RED SOIL - Analysis of Variance

Source	DF	SS	MS	F
Treatments	4	244.21	61.05	8.00**
Error	55	419.52	7.63	
Total	59	663.73		

- Duncan's Multiple Range, $S\bar{x} = (7.63/12)^{\frac{1}{2}} = 0.797$

No. of Means	2	3	4	5
SSR[2]	2.84	2.99	3.09	3.14
LSR	2.26	2.38	2.46	2.50

- Significant Difference

Depth (in.)	1	3	5	7	9
Means of T_T	(63.0)	59.0	60.3	60.9	64.7

BROWN SOIL - Analysis of Variance

Source	DF	SS	MS	F
Treatments	4	39.76	9.94	2.58*
Error	55	212.28	3.85	
Total	59	252.04		

- Duncan's Multiple Range, $S\bar{x} = (3.86/12)^{\frac{1}{2}} = 0.567$

No. of Means	2	3	4	5
SSR[2]	2.84	2.99	3.09	3.14
LSR	1.61	1.70	1.75	1.78

- Significant Difference

Depth (in.)	1	3	9	5	7
Means of T_T	(60.5)	58.0	58.7	59.1	59.2

1. Mean of T_S was the same for both soils therefore T_T was used.

2. Protection level, 5%

* $P < 5\%$, ** $P < 1\%$

Table 3. Soil Density/Compaction Procedure Relationship

Soil	Red	Brown	Red	Brown
Roller Index	18	18	60	60
Number of passes	5	10	15	15
Compaction level	less dense		dense	
Soil Density (means)	64.0	63.4	85.5	80.2

Table 4. Soil Density/Compaction Procedure Relationship - Statistical Analysis

Source of Variation	DF	SS	MS	F
Treatment	1	N/A	5587.35	97.69**
Soil	1	N/A	132.02	2.31
Treatment x Soil	1	N/A	84.02	
Error	56	3202.80	57.19	
Total	59	9006.18		

Duncan's Multiple Range, $S\bar{x} = (57.19/15)^{1/2} = 1.95$

Number of Means	2	3	4
SSR[1]	2.84	2.99	3.08
LSR	2.54	5.83	6.01

Significant Difference (not underscored by same line)

Soil	Brown	Red	Brown	Red
Density	Less Dense		Dense	
Means of γ_D	63.4	64.0	80.2	85.5

1. Protection level, 5%

** P < 1%

between the soils but there was between the compaction levels. This is noted in the table by the appropriate underscoring of the density means.

The impression of the early compaction trials was that the correlation between the soil density, as measured by the gamma-ray transmission equipment, and the firmness of the soil was poor. A cone penetrometer was used to check the correlation. Two scale readings were obtained for each site used in determining the soil density above. Using a calibration curve, the penetrometer readings were converted to values of cone resistance (Appendix 7-9). The mean of the two values was calculated and was paired with the appropriate observation of the density. The coefficient of determination (the square of the correlation coefficient) was determined (Table 5) for each soil at each compaction level, for both compaction levels for each soil, and finally for both soils at both compaction levels. In the first instance the correlation was very poor. With the addition of the other compaction level the correlation was greatly improved, especially in the case of the brown soil. The correlation with regard to both soils at both compaction levels was still good. There was a slight improvement in the case of the red soil by itself but a reduction in the case of the brown. It would appear that the soil density, if measured accurately, is a valid parameter of the soil for tillage experiments.

Table 5. Soil Density/Cone Resistance Correlation

Soil	Density	Coefficient of Determination - r^2		
Red	Less Dense	0.19	0.76	0.77
	Dense	0.06		
Brown	Less Dense	0.25	0.91	
	Dense	0.06		

CHAPTER 8

EXPERIMENTAL OBJECTIVES AND DESIGN

Literature Review Summary

The literature review revealed not only the present tillage technology but delineated appropriate areas for further inquiry. In addition, the basic objective of a tillage investigation should adhere to one observation in the first chapter; that is, the purpose of the inquiry should be to increase the energy efficiency of the tillage process. The objectives, however, cannot be stated without regard to the facilities which, in a tillage study, include the soil. Two other details, not yet discussed, are also required. These are the implications of sample variation and the kinematics of oscillation.

Vibratory tillage appears as a valid alternative to the conventional. Its potential appears to be in increasing the cultivating capacity without causing detrimental levels of mechanical impedance in the traffic sole. It may also provide a gain in the transmission efficiency of energy from the tractor to the tool. The possibilities of vibratory tillage altering the dynamic soil strength is obscure, especially at high travel rates. Obtaining greater capacity by increasing the travel rate avoids increasing the size of the tillage unit but, for rigid tools, the gain is penalized by the substantial increase in soil strength with the load rate. The potential of vibratory tillage appears to agree with the basic objective and, therefore, is a promising area of investigation.

It is evident that an analytical approach to vibratory tillage is not feasible, at least not for the present. Without a mechanics, the relationships of the dependent and independent variables must be determined through experimentation. In other words, the investigation must be a factorial experiment. It is expected that dimensional analysis will aid in the analysis of the results and that the dimensionless term, λ, will be useful in selecting levels of some of the mechanical factors.

With the exception of the mode of oscillation, the following relationships are suggested by the literature review for vibratory tillage. They also provide a concise summary.

$$\text{Power} = g(d,\dot{x}) + g'(t,f)$$

where d and t (draught and torque) are the independent variables in the following:

$$d,t = g(\psi,\alpha,L,B,\dot{x},f,A,\theta,D,S,\gamma,m).$$

A glossary of the symbols is given in Table 6. The variables or factors may be divided into two groups, mechanical and soil. A further division of the former is possible, such as static and dynamic. The first four (in the second relationship), for example, describe the shape of a simple tool. The next four are the mechanical factors of vibratory tillage.

The mode of oscillation was excluded from the above relationship and the proposed investigation as there was no facility for it with the equipment available. Complex tool shapes for inverting the soil were excluded on the basis of a conclusion of Chapter 2, which is that simple tillage tools pulverize the soil (without inversion) which is the most important aspect of the tillage process. One essential observation in the literature review is that the minimum energy, if it exists, should occur when λ is greater than 1 but less than 3. In order to determine an optimum at least three observations are required; that is, the levels of λ should be 1, 2 and 3. The relationship of λ and the mechanical factors of $\dot{x}$, f and A is noted in another section in this chapter entitled, Kinematics of Oscillation.

Table 6. Glossary of Symbols, Independent Variables or Factors.

Variables	Factors	Description
ψ		approach angle of the leading edge of the tool,
α	R	rake angle of the tool,
L		length of the tool,
B		width of the tool,
D		depth of the cut or operation in the soil,
$\dot{x}$		travel rate of the implement (x_i),
f	F	frequency of oscillation
A	A	amplitude of oscillation,
θ	H	plane of oscillation
S	S	soil type,
γ	C	soil density,
m		moisture content.

Experimental Design - Soil

The number of variables or factors and their levels in the experimental work was restricted because of the lack of information on the variation of the soil resistance or reaction within and between soil preparations. That is, a systematic variation of the reaction would affect the validity of the results. It was necessary, therefore, to have an experiment in two parts, with the first part primarily to explore these variations. In order to proceed with Part 1 as soon as possible, a tool that was available at the time was used. This tool was a vertical wedge in which the factors ψ,α,L and B were fixed. Part 2 of the experiment was a larger experiment with more factors using a horizontal share.

The decision to include two soil types was based on the observation that little is known of the relationship of soil texture and vibratory tillage. This decision, taken in the inchoate period because of the approach of winter, restricted the experiment slightly. Handling two soils rather than one took time that might not have been incurred had a mechanical factor been chosen instead.

The other two soil factors in the relationship noted previously were density and moisture content. The time required to prepare the soil was considerable and therefore their inclusion had important consequences. The inclusion of two levels of soil density seemed to be the minimum. With regard to the moisture content, only the minimum level could be used in Part 1 because drying the soil was impractical; that is, water could not be added between the minimum moisture contents of Parts 1 and 2 because it could not be removed. For different levels of moisture in Part 2, the procedure envisaged was to complete all the replicates at one level, then repeat them at a higher level.

Experimental Design - Part 1

In order to test the variation in the soil resistance between soil preparations (Part 1), at least two replicates would be required. For the two soil densities then, four soil preparations for each soil would be needed. In allocating plots within the soil tank, three per soil-tank length or per pass of the vertical wedge seemed possible. As to the number of passes, this was a function of the width of the lateral positioning of the tool and the width of the soil disturbance. From Payne (67) the latter (W) is related to the depth of tillage (D) by the following;

$$D = W\ \tan(45-\phi/2),\ \text{where}$$

$$W = (W_T/N) - B - w/2$$

where W_T is the positioning width of the tool,

w is the width of the "guard strip" between passes,

N is the number of passes per soil preparation.

The angle of shearing resistance for the soils was unknown but would be approximately 20°. W_T was 51 in. while one in. seemed an adequate "guard strip". The calculated depth of tillage for four passes was 3.85 or four in. Though a depth of four in. is not representative of ploughing, it is of cultivating when simple tools are used. The alternative was to reduce the number of passes to three but this would provide for only nine samples or observations for each replicate.

Though the main purpose of Part 1 was to explore variations in the soil resistance, some information was sought with regard to the mechanical factors as well. The two purposes conflict. For the former, all factors should be held constant while for the latter, they should not. The compromise may be noted in Table 7. This arrangement provides for estimates of any linear and quadratic trends across the tank, as well as residual variations between passes. Only one mechanical factor could be included in Part 1 and, largely for convenience, the amplitude of oscillation was chosen. Frequency would have served equally well.

One of the levels of amplitude selected was zero. The main purpose was to enhance the test for the order of tillage. The tool could pass through the soil in only one direction and this procedure could introduce a bias. The secondary purpose was to provide at least one comparison in the experiment for a comparison between a rigid and a vibratory tool. Extensive comparisons between the two kinds of tools are not warranted because of the work of Eggenmüller (27) and other investigators. The other levels of amplitude correspond to λ of 2 and 3. Travel rate and depth were not selected because they could not have a level of zero in the experiment. Other reasons are noted below.

The only other factor not already accounted for is the plane of oscillation and for a vertical wedge it was unlikely that it would affect the results to any extent. For Part 1, a horizontal plane of oscillation was used.

Table 7. Part 1 Experimental Design - 3 Levels of Amplitude

Replicate	1	2
Tank Position		
a cross/down	a b c	a b c
1	2 2 2	0 2 1
2	0 2 1	2 2 2
3	0 2 1	2 2 2
4	2 2 2	0 2 1

Experimental Design - Part 2

The experimental design of Part 2 depended to a considerable extent on the results of Part 1. Though a chronological exposition has merit, commenting on the design in this chapter is preferred. In Part 2, a share or horizontal tool, five in. wide, was used. With this width, twice as many passes, and therefore twice as many plots (8 x 3), were possible for each soil preparation as with the vertical wedge. Although eight passes with a six-in.

share would have been less than W_T, a five-in. share was used in order to increase the distance between the outside passes and the edge of the uncompacted soil. This was one of the results of the Part 1 experiment.

The edge effect of the share was avoided by preparing the soil with the furrow plough. In this way, the results may be applied to a share of any width provided the edge effect can be either ignored, or some allowance made for it. The former is valid for wide tools if the depth is not large. There is one other advantage. Soil failure will occur only in one plane and this was expected to simplify the analyses of results.

In a 24-plot replicate (8 x 3) a 3×2^3 factorial provides the maximum number of factors, namely four. To include as many factors within the experiment as possible was desirable. The particular design chosen was plan 6.10 per Cochran and Cox (20). As noted by these authors, "In plan 6.10 the interactions BC, BD, and CD, between pairs of factors that occur at 2 levels, are partially confounded with 8/9 relative information, while 5/9 relative information is retained on the interactions ABC, ABD and ACD." The choice was another result of Part 1. The problem was that a gradient in the soil resistance or reaction existed across the tank with the maximum occurring at the centre. The authors continue, "Only the balanced design which required 3 replications is recommended." For Part 2 then, the number of soil preparations for each soil was six. Because of the total number of soil preparations and the difficulties experienced with the equipment, there was no opportunity for repeating Part 2 at a higher moisture content.

In some respects, the choosing of the four mechanical factors to be included in the experiment was difficult. Frequency and amplitude were selected because they define the level of the dimensionless term, λ. In addition, a quadratic relationship between either factor and the draught or torque was expected. To have either constant without knowing their proximity to a maximum would limit the value of the results. The plane of oscillation is an important factor and it too was expected to have a maximum response. The fourth factor was the rake angle and was included because of its influence on the clod size distribution. Its effect on the draught and torque, or lack of it, would be of particular interest. Of the mechanical factors held constant, only depth and travel rate were expected to influence the results to any great extent. With regard to the former, soil strips with different depths could not be cut with the equipment used. As for the travel rate, the maximum was well below the conventional tillage speeds and, therefore, levels in this range would have been of limited value. The reason for the low travel rate is noted later.

Kinematics of Oscillation

Eggenmüller (27) has written, "The appropriate method for assessing oscillation is to plot the oscillation path." His "oscillation path" was based on a sinusoidal motion of the tool superimposed on a uniform travel rate of the cart. Though both motions are a simplification, they are reasonable if the length of the connecting rod is large in comparison to the eccentricity of the crank and if the acceleration of the cart is small relative to the distance traversed. The horizontal displacement of the tool with respect to the cart from inspection of Figure 27 is:

$$x_t = A\cos\delta\cos\theta$$

where A and θ are defined in Table 6,

δ is the angular displacement of the crank $\left(\cos\delta = \cos(2\pi-\delta)\right)$

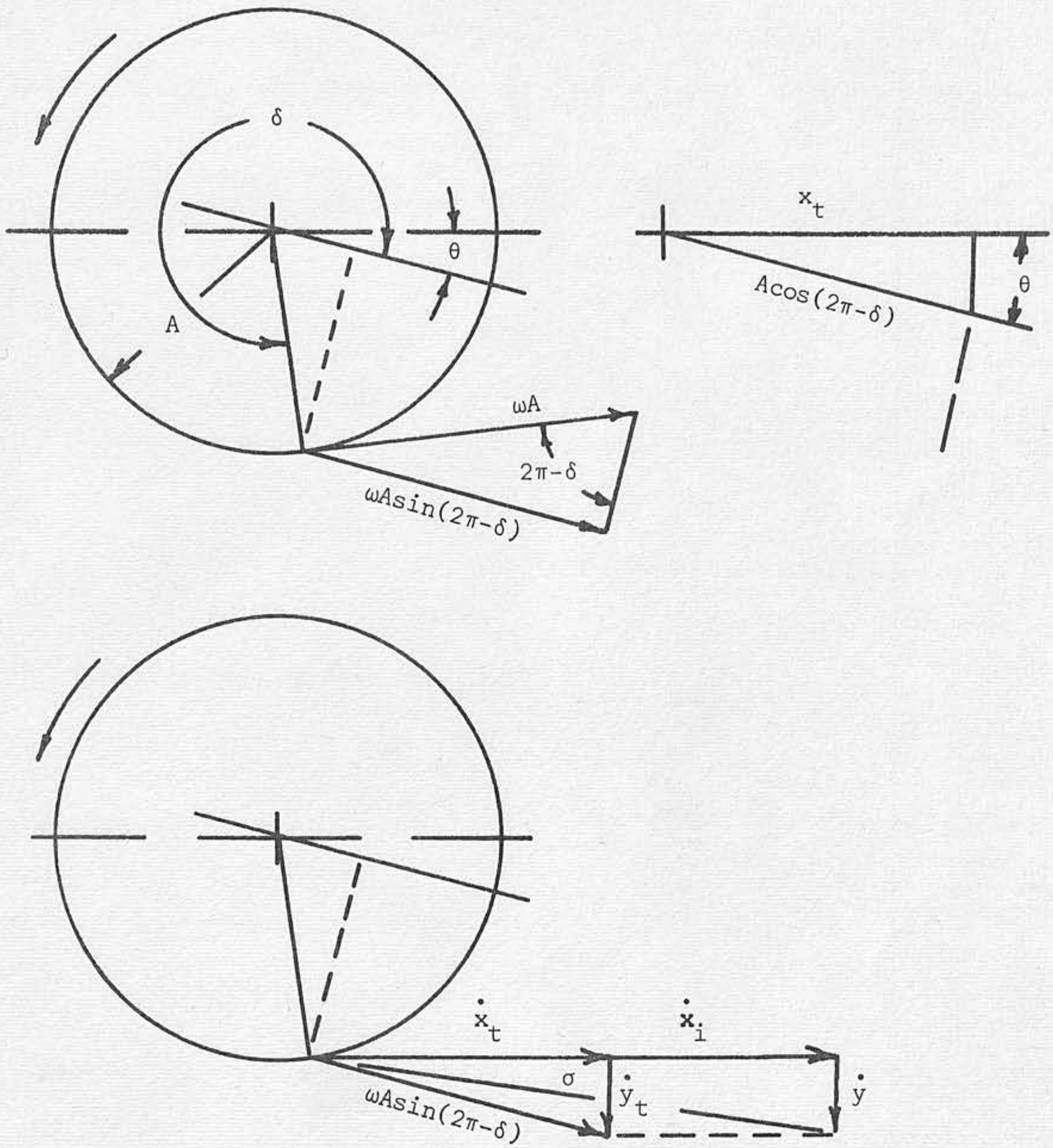


Figure 27 Kinematics of Vibratory Tillage

If the horizontal displacement of the tool carrier is x_i, then the horizontal displacement of the tool with respect to the soil is;

$$x = x_i + A\cos\delta\cos\theta \qquad -1$$

Similarly, the vertical displacement of the tool with respect to the soil is;

$$y = y_t = -A\cos\delta\sin\theta \qquad -2$$

The maximum value of y occurs whenever $\cos\delta = 1$. With some rearrangement, the following specifies the inclination of the plane of oscillation when the maximum value of y is defined.

$$\theta = \sin^{-1} y/A. \qquad -3$$

The angular displacement of the crank is defined as

$$\delta = \omega T \qquad -4$$

where ω is the angular velocity of the crank ($f = 2\pi\omega$),

T is the time interval.

By substituting for δ in equations 2 and 3, the derivative with respect to time, when δ is resubstituting, is;

$$\dot{x} = \dot{x}_i + \omega A\sin\delta\cos\theta \qquad -5$$

$$\dot{y} = \qquad \omega A\sin\delta\sin\theta \qquad -6$$

where $\dot{x}$ is the horizontal velocity and $\dot{y}$ the vertical when $3\pi/2<\delta<2\pi$. Also;

$$x_i = \dot{x}_i T = \dot{x}_i \delta/\omega \qquad -7$$

As can be seen in Figure 27 the direction of the tool with respect to the soil is given by;

$$\sigma = \tan^{-1} \dot{y}/\dot{x} \qquad -8$$

The dimensionless ratio λ is defined by Kofoed (52) as;

$$\lambda = \ell/2r$$

where ℓ is the horizontal motion during one cycle ($\delta = 2\pi$). From equation 7, then, ℓ is equal to $\dot{x}_i 2\pi/\omega$. As r is equal to the amplitude, A;

$$\lambda = \pi\dot{x}_i/\omega A \qquad -9$$

By substituting for δ in equation 5, the derivative with respect to time when δ is resubstituted is;

$$\ddot{x} = \omega^2 A\cos\delta\cos\theta \qquad -10$$

where $\ddot{x}$ is the horizontal acceleration ($\ddot{x}_i = 0$).

Travel Rate

The maximum frequency of the vibratory drive was 37½ cps or a rotational speed of 75π radians/sec. The maximum amplitude was 0.0366 ft. In order to obtain a λ of 1, the maximum travel rate is defined by equation 9 of the prior section; that is,

$$x_i = \omega A/\pi = (75\pi)\ 0.0366/\pi$$
$$= 2.74 \text{ ft/sec or } 1.87 \text{ mph.}$$

The continuing problems with the vibratory drive and the instrumentation during Part 1 indicated that the maximum frequency could not be used with the maximum amplitude. With the modifications described in Chapter 6, there was a chance that the equipment would survive the combination of maximum frequency (37½ cps) and an amplitude of 0.020 ft. This was equivalent to $\lambda \simeq 2$ for Part 1. To include a level of λ of 1, it was necessary to reduce the travel rate. For Part 2, then

$$\dot{x}_i = (75\pi)\ 0.020/\pi$$
$$= 1.5 \text{ ft/sec or } 1.0 \text{ mph.}$$

Frequency and Amplitude

For Part 1, the two levels of amplitude used, other than zero, were 0.018 and 0.012 ft. The respective values of λ were 2 and 3 for a travel rate of 2.74 ft/sec and the maximum frequency of 37½ cps. At the time, it was expected that the modifications noted in the prior section would permit the inclusion of the maximum frequency and amplitude combination in Part 2. The delay incurred by these changes was minimized by proceeding with Part 1 using the amplitudes noted above and avoiding the critical combination ($\lambda = 1$).

For Part 2, three levels of frequency and two of amplitude were used. The levels selected for the travel rate of 1.5 ft/sec were equivalent to λ of 1, 2 and 3, and 2', 4 and 6. The λ of 2 in the first group is distinguished from λ of 2 in the second group (by the use of ') because they are defined by different combinations of frequency and amplitude. The coincident was deliberate and the purpose was to ascertain how useful λ is as an independent term.

The opposite arrangement in the number of levels of frequency and amplitude was possible and in addition could be selected to provide the same values of λ as noted above. This arrangement was rejected because of the anticipated quadratic relationship between the dependent factors of draught and/or torque and the independent factor of frequency. As indicated in the literature review, the relationship may be a polynomial rather than an exponential one; that is, there may be an optimum frequency with respect to the dependent factors.

The maximum level of frequency and amplitude has already been specified in the prior section. The other levels may be seen in Table 8. They were calculated using equation 9, a travel rate of 1.5 ft/sec and the levels of λ noted above. As may be seen, specifying the frequency in this manner results in an uneven increment between the levels

Table 8. Dimensionless Ratio, λ, Frequency and Amplitude - Part 2

Frequency (cps)/Amplitude (ft)	0.020	0.010
37-1/2	1	2'
18-3/4	2	4
12-1/2	3	6

Plane of Oscillation and Rake Angle

The maximum tilt of the plane of oscillation of the vibratory drive was 40°. In order to achieve equal vertical displacement for both levels of amplitude, the tilt must differ. The maximum vertical displacement is defined by equation 3 for the minimum amplitude;

$$\begin{aligned} y &= 0.010 \sin 40^{\circ} \\ &= 0.00643 \text{ ft.} \end{aligned}$$

The value of θ when the amplitude is 0.020 ft is;

$$\begin{aligned} \theta &= \sin^{-1} (0.00643/0.020) \\ &= 18\tfrac{1}{2}^{\circ}. \end{aligned}$$

The rake angle and, for that matter, all other dimensions of the vertical wedge were fixed for Part 1. For the horizontal tool in Part 2, the 3° rake angle was the smallest that was practical. For a horizontal plane of oscillation, it was the nearest to pure cutting of the soil that was feasible. The other rake angle was 20° and was selected to cause rupturing of the soil as well as cutting for all levels of the other factors. Though excessive pulverization for every level of the other factors was to be avoided, this could not be known without running a number of trials. In view of this the selection was based primarily on experience.

Tool Displacement

In order to plot the tool displacement for one cycle of oscillation, the horizontal displacement of the tool carrier or cart was calculated using equation 7 for δ of $\pi/2$ and for λ of 1, 2 and 3. The displacement is the same for λ of 2', 4 and 6. The horizontal displacements of the tool with respect to the soil were subsequently calculated using equation 1 for θ equal to zero and are shown in Figure 28. In this instance, the vertical displacement is for illustration purpose only.

For the tilted plane of oscillation, the horizontal and vertical displacements of the tool with respect to the soil were calculated using equation 2 for δ of $\pi/2$ and for the appropriate values of θ. As an aid in plotting, the velocities of the tool were calculated using equations 5 and 6 and subsequently the directions of the tool using equation 8 for δ of zero and π. The directions of the vectors are shown in Figure 29 along with the tool displacement.

It can be seen in Figure 28 that only when λ is 1 is there reversal of the tool in the soil. For λ of 2 and 2', there is no motion in the soil for the crank displacement of π to $3\pi/2$. For other values of λ, the motion with respect to the soil is always in the same direction. For the tilted plane of oscillation (see Figure 29) there is some reversal for λ of 2 and 2'. It is also evident that the two displacements are not similar. These minor distinctions are not valid because the amplitude of oscillation, while tilling the soil, differed in some instances from the levels of 0.018 and 0.012 ft for Part 1 and 0.020 and 0.010 ft for Part 2. The changes in the amplitude were caused by rotation of the shank due to clearance in the "sliding" bearings (see Chapter 6). As long as the soil pressure on the tool was in the same

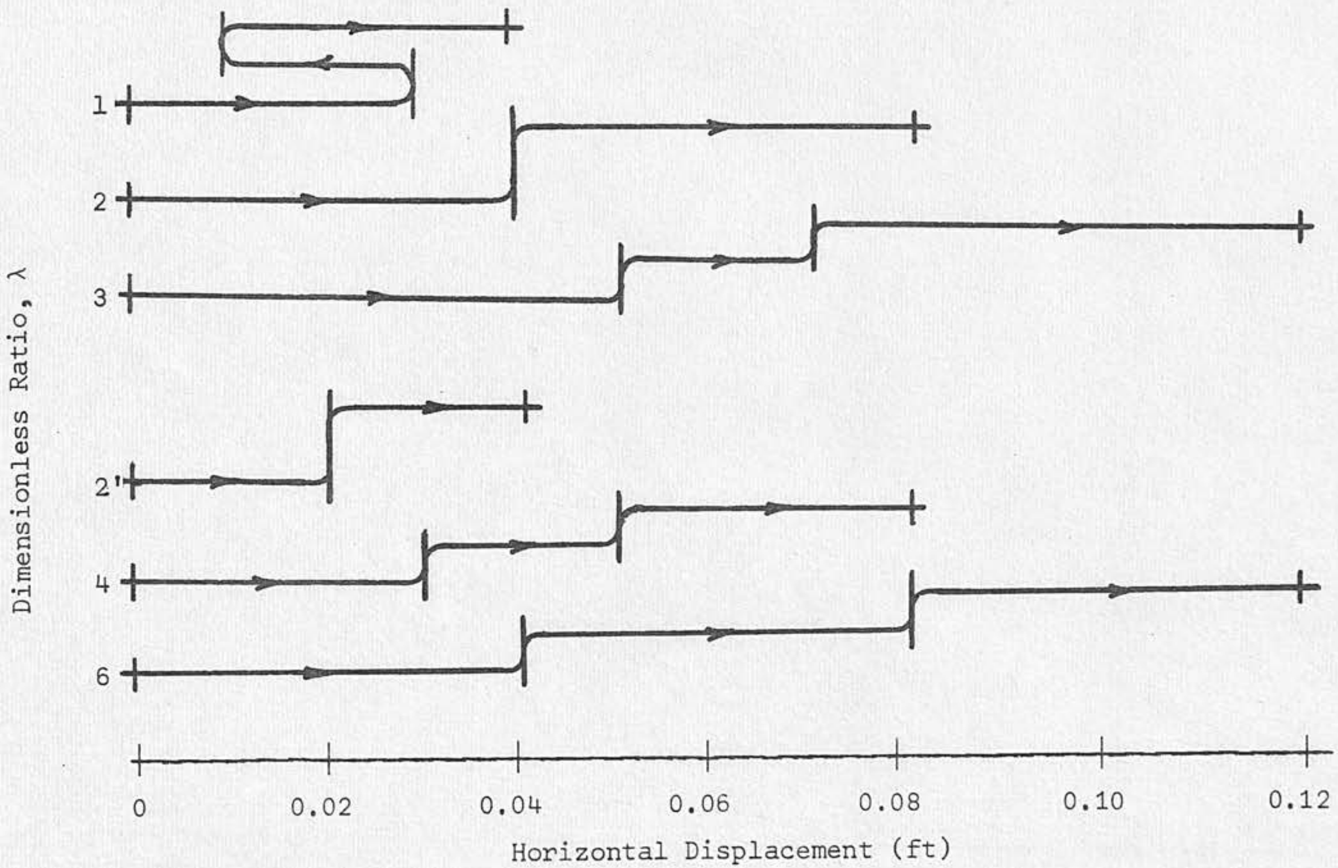


Figure 28 Tool Displacement, horizontal plane of oscillation

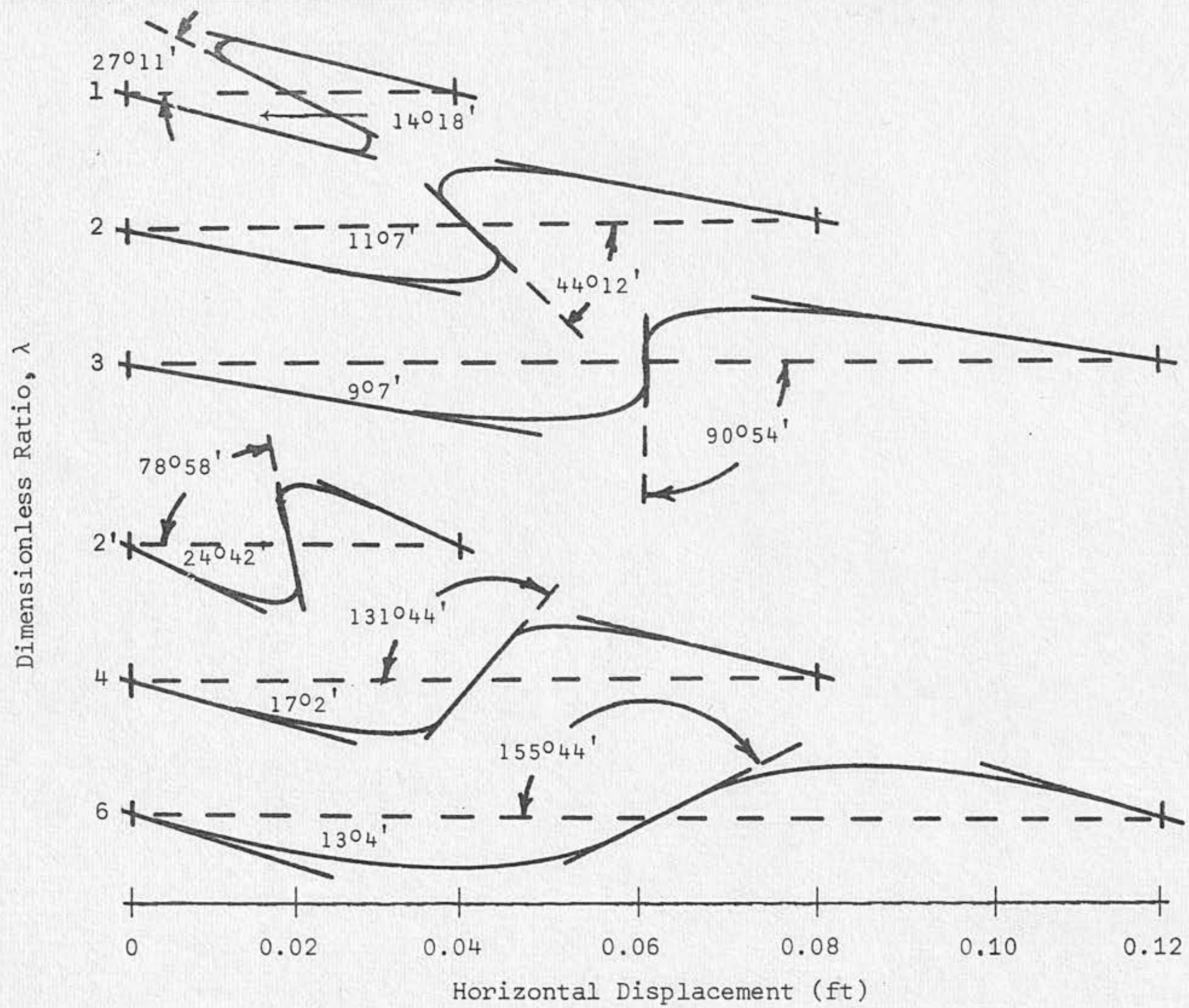


Figure 29 Tool Displacement, tilted plane of oscillation

direction, and was larger than the inertia of the shank, rotation would not occur and there would be no lost motion or reduction in amplitude. Ignoring for the moment the inertia of the shank, it follows from this that there would be no lost motion for λ greater than 2 because the soil resistance would always be in the one direction and the nominal and actual amplitudes would be the same. For the tilted plane of oscillation and λ of 2 or 2', the amplitude would reduce just sufficiently so that the soil resistance would always be in the same direction. In other words, there would be no reversal of the tool for λ of 2 as indicated in Figure 29. With regard to λ of 1 and 2', it is necessary to note the effect of the inertia of the shank before commenting on the changes in the amplitude.

As noted in Chapter 6, the mean acceleration was

$$\ddot{X}' = \omega^2 A/\pi$$

or

$$R = W\omega^2 A/\pi g$$

where R is the inertia reaction, and

W is the weight of the shank and share ($\simeq$ 11 lb).

For the maximum frequency and an amplitude of 0.020 ft, (λ of 1), the inertia reaction from the equation above is nearly 112 lb. The centre of gravity of the tool was approximately one half of the distance between the share and the "sliding" bearings. That is, if the soil resistance on the share was greater than 56 lb, then there would be no rotation of the shank. For the nominal amplitude of 0.010 ft, the critical soil resistance would be 28 lb. The draught values obtained in Part 2 suggest that only for the maximum frequency and amplitude would the critical soil resistance be exceeded and this would be largely confined to the less dense red and brown soils; that is, for λ of 2' there would be no reversal of the tool as already noted for λ of 2. For λ of 1, the rotation of the shank would reduce the amplitude from 0.020 ft in spite of the large inertia reaction. The value of λ for this combination cannot be estimated. It would be greater than 1 but considerably less than 2. For convenience, this combination of frequency and amplitude is referred to as λ of 1 even though it was somewhat larger than this.

CHAPTER 9

ANALYSIS OF RESULTS AND DISCUSSION

Variation of Results

The minimum, maximum and the mean of the draught, torque and frequency observations are given in the Appendix, Tables 9-1 to 9-4 for Part 1 and Tables 9-5 to 9-8 for Part 2. Instead of the minimum and maximum travel rate, the observations at the beginning, v and the end, v' of the plot run are given, indicating the number of occasions when $v \neq v'$ and the magnitude of the inequality. The soil tilth after tilling the plots in Part 2 is illustrated in Plates 10 to 25.

Some of the variation in the means of the draught and torque (and the drawbar and shaft horsepower) cannot be accounted for by the levels of the soil and mechanical factors; that is, there is a residual variation which obscures the relationships between the dependent and independent variables or factors. Statistical analysis provides a method for allocating the variation between the factors provided the variation is random; that is, the variation is not systematic. An example of avoiding a systematic variation was the procedure used to determine the base frequency of the torque transducer (see Chapter 6) even though the procedure increased the random variation considerably. Except for the maximum level of amplitude at the maximum frequency, all other sources of variation associated with the mechanical factors, and this includes the sensing and recording apparatus, were expected to be random.

Sources of Variation - Soil

The Part 1 experiment was conducted primarily to determine if a systematic variation occurred within the soil. It was expected that, if such a variation occurred, it would be associated largely with the soil density. No measurable systematic variation was expected for either the soil type (texture) or moisture content because of the amount of mixing that was involved in preparing the soil. The soil was subject to drying, but frequent monitoring and periodic applications of water maintained the moisture content at a reasonable uniform level.

The sources of variation for the soil may be divided into the following:

- position of plots within the pass (within the block),
- position of the passes (blocks) within the soil tank (within replicate), and
- between fillings of the tank (between replicates).

The data used (Appendix Table 9-9) in the analyses* was primarily the drawbar horsepower (DHP) because it appeared to be more sensitive to variations in the soil than the torque or shaft horsepower (SHP). The draught could have been used but it would not have included any variation that might have occurred in the travel rate. The analyses were carried out assuming the linear model;

$$y_{ij} = m + a_i + b_j + e_{ij}$$

where m is the mean of the observations y_{ij},

a_i is the effect of the treatment i,

$i = 0, 1, 2,$

b_j is the effect of the pass or block j,

$j = 1, 2, 3, 4,$

e_{ij} is the residual variance, σ^2

* Dr. R.M. Cormack, Univ. of Edinburgh, conducted a number of the analyses.

When an order of tillage is included, the model is:

$$y_{ijk} = m + a_i + b_j + o_k + e_{ijk},$$

where o_k is the effect of the order k,

$k = 1, 2, 3.$

The order of tillage arises because only one direction of the tool was possible and the tillage of the first plot in the pass or block had to precede the second, and similarly the tillage of the second plot had to precede the third or last. The "effects" of (or the contributions to the variance of the observation by) the treatments and blocks may be seen in Table 9 for each soil, density, and replicate, and in the case of the red soil, the "effect" of the tillage order as well. The "effects" were estimated by multiplying each of the twelve observations by an appropriate coefficient (see Appendix Table 9-10) and then summing for each "effect". The residual variance was obtained by multiplying each "effect" times the appropriate sum of the observations, subtracting the result from the sum of squares of the twelve observations and dividing the difference by the residual-degrees of freedom. The latter, with and without the tillage order, were respectively four and six.

There is some heterogeneity of variance for the DHP; that is, the residual variance is not consistent, and is large for the dense red soil. There is some suggestion that the second replicate was more variable (larger residual variance) than the first though the opposite occurred for the less dense brown soil. The large residual variance of the dense red soil is attributed to the formation of large clods which were quite durable. The clods were formed while compacting the soil to the higher level. The clods caused the boundary between the tilled and untilled soil to be very irregular. In the

Table 9: Contributions to the Variance of the Drawbar Horsepower or "Effects" - Part 1

Soil	Repli-cate	Mean	Treatments			Blocks				Orders			
		m	a_0	a_1	a_2	b_1	b_2	b_3	b_4	o_1	o_2	o_3	σ^2
Without Order of Tillage													
Less Dense Red	1	.425	.259	-.078	.052	.096	-.047	.005	-.054	---	---	---	.0004
	2	.516	.369	-.111	.074	.147	-.136	-.101	.091	---	---	---	.0087
Dense Red	1	1.674	.475	-.346	1.086	-.903	.364	.784	-.246	---	---	---	.3336
	2	1.651	.726	-.198	.065	-.039	.487	-.675	.227	---	---	---	.9476
	Mean					-.178	.167	.003	.004				
Less Dense Brown	1	.491	.290	-.074	.007	.033	.093	.077	-.133	---	---	---	.0164
	2	.525	.316	-.104	.101	.021	-.158	.019	.118	---	---	---	.0054
Dense Brown	1	1.134	.830	-.159	-.195	-.228	.416	.041	-.229	---	---	---	.0328
	2	1.314	.745	-.244	.229	.242	-.071	-.502	.331	---	---	---	.1257
	Mean					.017	.070	-.091	.022				
With Order of Tillage													
Less Dense Red	1	.425	.259	-.078	.055	.068	-.047	.005	-.054	.001	.001	-.002	.0159
	2	.516	.321	-.096	.062	.107	-.121	-.086	.076	.033	-.030	-.003	.0207
Dense Red	1	1.674	.678	-.094	-.304	-1.017	.292	.712	-.174	-.131	.144	-.013	.5048
	2	1.651	.868	-.295	.313	.013	.389	-.772	.324	-.044	.195	-.150	.7839

less dense soil, the undisturbed soil was smooth. In the dense soil, it was difficult to locate the boundary because it was evident that some clods had been disturbed by the tool but were not loose. The face of the boundary was not smooth while the slope varied widely.

The inclusion of the order of tillage "effect" for the red soil increased the residual variance except for the second replicate of the dense red soil. The residual variance or mean square for the red soil, with and without the "effect" for a tillage order, may also be seen in Table 10. The differences between the sum of squares with and without the order "effect" were not significant (see Table 11); that is, there was not a systematic variation within the block due to the order "effects". In view of this, and because the compacting techniques were similar for both soils, the brown soil was not analyzed for the order "effect".

The means of the block "effects" are illustrated in Figure 30 together with the density gradient as determined from density measurements in Chapter 7. The latter was obtained by considering the positions across the tank as blocks. With the exception of b_3 "effect" for the brown soil, there is a similarity between the block "effects" and the density gradient across the tank. Neither, however, were significant (see Table 12).

Though the order of tillage did not contribute to the residual variance, the possibility that tillage in one plot would affect another was examined. This was accomplished by comparing the DHP results when the amplitude a_2 was preceded by the amplitude a_0 (zero) in one case, and by a_2 in another. At the lower density level (Table 13) there is the suggestion that the DHP does depend on the preceding treatment. This does not appear to be a valid conclusion because;

Table 10: Residual Variation of the Drawbar Horsepower (Part 1) for the Red Soil, with and without an Order of Tillage.

Source of Variation	DF	Replicate 1 SS	Replicate 1 MS	Replicate 2 SS	Replicate 2 MS
Less Dense Red Soil					
Without Order "Effect"	6	0.19159	0.03193	0.20703	0.03450
Residual	6	0.00243	0.00040	0.05227	0.00871
Total	12	0.19402		0.25930	
With Order "Effect"	8	0.13062	0.01633	0.17662	0.02208
Residual	4	0.06340	0.01585	0.08268	0.02067
Total	12	0.19402		0.25930	
Dense Red Soil					
Without Order "Effect"	6	4.17942	0.69657	0.10270	0.01712
Residual	6	2.00130	0.33355	5.68560	0.94760
Total	12	6.18072		5.78830	
With Order "Effect"	8	4.93002	0.61625	0.39348	0.04918
Residual	4	2.01912	0.50478	3.13552	0.78388
Total	12	6.94914		3.52900	

Table 11: Differences in the Sum of Squares of the Drawbar Horsepower (Part 1), with and without an Order of Tillage for the Red Soil - Analysis of Variance.

		Replicate 1			Replicate 2		
Source of Variation	DF	SS	MS	F	SS	MS	F
Less Dense Red Soil							
Difference	2	0.06097	0.03049	<1	0.03041	0.01520	<1
Residual	4	0.01585	0.06340		0.08268	0.02067	
Dense Red Soil							
Difference	2	0.75060	0.37530	<1	0.29078	0.14539	<1
Residual	4	2.01912	0.50478		3.13552	0.78388	

Table 12: Block "Effects" and Density Gradient - Analysis of Variance

		Red Soil			Brown Soil		
Source of Variation	DF	SS	MS	F	SS	MS	F
Block "Effects"							
Blocks	3	0.2338	0.0779	<1	0.0558	0.0186	<1
Residual	6	----	0.3226			0.0451	
Density Gradient							
Blocks	4	521.98	130.49	<1	434.00	108.50	<1
Residual	25	4717.49	188.70		3138.07	125.53	
Total	29	5239.47			3572.07		

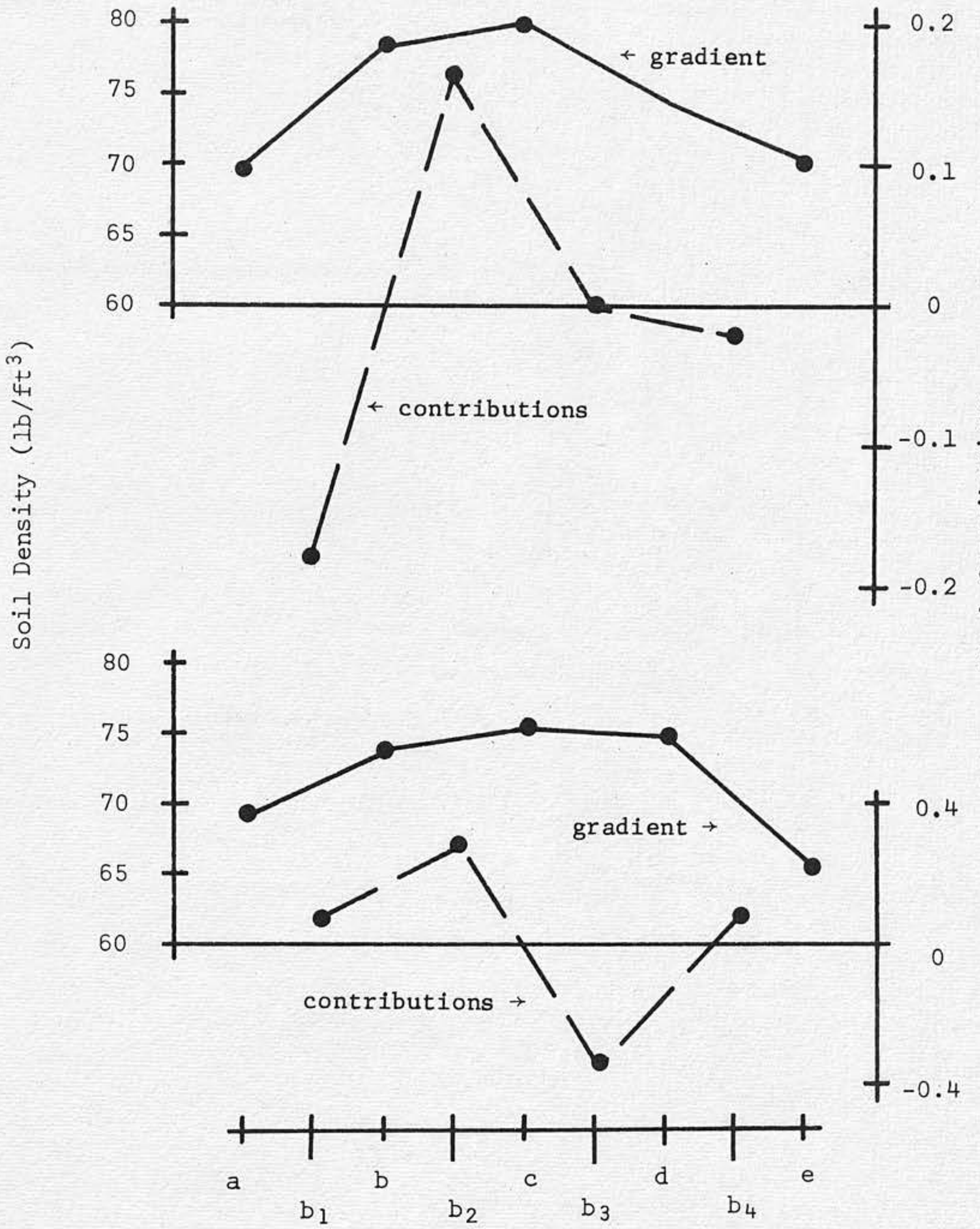


Figure 30 Block Contributions (mean) to the Variance of the Drawbar Horsepower (Part 1) and Soil Density Gradient across the Tank; top- red soil, btm- brown soil.

Table 13: Drawbar Horsepower (Part 1) using the Same Amplitude when the Preceding Plot was Similarly and Differently Treated - Analysis of Variance.

		Less Dense Soils			Dense Soils		
Source of Variation	DF	SS	MS	F	SS	MS	F
Replicates	1	0.0064	0.0064	1.0	0.0137	0.0137	<1
Blocks	3	0.0657	0.0219	3.5	1.4282	0.4761	4.5*
Soils	1	0.0161	0.0161	2.6	1.5098	1.5098	14.2**
Treatments (preceding)	1	0.0295	0.0295	4.7	0.0624	0.0624	<1
Soils x Treatments	1	0.0062	0.0062	<1	0.1321	0.1321	1.2
Residual	8	0.0504	0.0063		0.8505	0.1063	
Total	15	0.1743			3.9967		

* $P < 5\%$, ** $P < 1\%$

Table 14: Percentage Change in the Drawbar Horsepower (Part 1) of the First Plot Compared to the Second Plot when Similarly Treated.

	Block Positions							
	1	4	2	3	1	4	2	3
Soil	Red				Brown			
Less Dense	6.9	-9.5	-14.5	-6.2	-13.2	0	38.2	75.0
Dense	72.6	7.5	38.5	-6.0	-30.4	13.0	-7.2	0

- there is no evidence of this phenomenon in the dense soils,
- Gumenskii and Kamarov (38) observe that the dimensions of the liquefaction zone is only several millimeters thick (plots exceeded ten feet in length), and
- there is no consistent percentage change in the DHP (Table 14 - comparing one plot to another when similarly treated).

The analyses (Table 13) indicate that, for both densities, there is no "between replicate" variance. The blocks, however, are a source of variation for dense soils with the centre blocks requiring more DHP than those on the outside. Another disturbing observation is the magnitude of the variation in the DHP for similarly treated plots (see Table 14).

Components of Variation - Soil

For the twelve observations from each filling of the tank or replicate in Part 1, one **estimates** the mean, two the treatments, and three the blocks, while the remaining six estimate the residual variation when the order of tillage is not included. Of the six degrees of freedom for the redisual, four are provided by comparisons within the uniformly treated blocks and two by comparisons between the two comparably treated plots in the other two blocks. The overall variation may be partitioned in the following manner;

- mean with 1 df (degree of freedom),
- treatments (ignoring blocks) with 2 df,
- blocks (adjusted for treatments) with 3 df,
- residual variation between blocks with 2 df, and
- residual variation within blocks with 4 df.

If the blocks are not taken out as a separate factor, but are included in the residual, then the last three sources are "pooled" and it is this residual which would be used to calculate the F-ratio. The data used in the analyses was the total horsepower (unadjusted for the friction in the drive). The F-ratio (Table 15) was reduced in most cases when the residual was pooled with the blocks and in particular when the blocks were significant as in the case of the dense red soil. The "pooling" with blocks increased the heterogeneity of variance between the two densities for the red soil but did not alter appreciably the other comparisons. In view of the above, it was considered essential that blocks be regarded as a fixed factor in the Part 2 experiment. This was accomplished by using a design from Cochran and Cox (20). The design resulted in some loss of information (see Chapter 8).

Heterogeneity of Residual Variance

One of the assumptions of analysis of variance is that the residual is homogeneous or has a common variance. Cochran and Cox (20) state that, "As a rule the failure of an assumptoin will affect both the significance levels and the sensitivity of F- and t- tests." The frequent result of such a failure (heterogeneity of the residual variance), according to these authors, is that, "....too many significant results are obtained" and that, "....the inflexible use of say the 5% significance level to divide the effects into those that are regarded as "real" and those that are not is hardly justifiable." Having regard for this advice, the draught for Part 1 for the two soils and two densities were analysed separately. This was also the procedure used for the Part 2 results. As the residual variation of the THP was homogeneous with respect to the soil density in Part 1, only separate analyses for the soils were made.

Regression Analyses

Though the analysis of variance for each soil and density avoids violating the assumption of a common residual variance, it precludes

Table 15: Total Horsepower (Part 1) with and without Pooling of the Blocks with the Residual - Analysis of Variance.

Source of Variation	DF	Replicate 1 SS	MS	F	Replicate 2 SS	MS	F
Less Dense Red Soil							
Treatments	2	14.253	7.126		13.943	6.972	
Blocks	3	0.357	0.119	4.2	0.116	0.039	<1
Residual between	2	0.055	0.028		0.323	0.162	
Residual within	4	0.052	0.013		0.400	0.100	
Treatments	2			396.			58.
Residual pooled	6	0.107	0.018		0.723	0.121	
Treatments	2			137.			75.
Pooled with blocks	9	0.464	0.052		0.839	0.093	
Dense Red Soil							
Treatments	2	13.176	6.588		21.100	10.550	
Blocks	3	6.317	2.105	11*	4.550	1.517	126***
Residual between	2	0.390	0.195		0.023	0.012	
Residual within	4	0.127	0.032		0.453	0.113	
Treatments	2			77.			134.
Residual pooled	6	0.517	0.086		0.476	0.079	
Treatments	2			9.			19.
Pooled with blocks	9	6.834	0.759		5.026	0.558	

* P < 5%, *** P < 0.5%

Cont'd.

Table 15: (cont'd)

Source of Variation	DF	Replicate 1 SS	MS	F	Replicate 2 SS	MS	F
Less Dense Brown Soil							
Treatments	2	13.345	6.672		15.086	7.543	
Blocks	3	0.211	0.070	1.5	0.693	0.231	<1
Residual between	2	0.095	0.047		0.910	0.455	
Residual within	4	0.184	0.046		1.627	0.407	
Treatments	2			145.			17.
Residual pooled	6	0.279	0.046		2.537	0.423	
Treatments	2			124.			18.
Pooled with blocks	9	0.490	0.054		3.230	0.359	
Dense Brown Soil							
Treatments	2	12.670	6.335		22.356	11.178	
Blocks	3	0.460	0.153	2.3	0.801	0.267	1.7
Residual between	2	0.443	0.222		0.270	0.153	
Residual within	4	0.267	0.067		0.773	0.193	
Treatments	2			53.6			64.
Residual pooled	6	0.710	0.118		1.043	0.174	
Treatments	2			48.7			54.
Pooled with blocks	9	1.170	0.130		1.844	0.205	

comparisons between the two soils and densities. According to Steel and Torrie (87) the linear trend, however, may be compared by calculating the appropriate regression coefficients (b and b') and testing for their homogeneity by a t-test, that is;

$$t_{.05} \geq (b - b')/(v + v')^{1/2}$$

where v and v' are the variances of b and b'. Since the variances v and v' must be the same or reasonably so, this precluded, in some instances, the opportunity for making a comparison.

<u>Draught of the Vertical Wedge - Part 1</u>

In Part 1, two blocks in each replicate contained information with regard to the effect of the treatment amplitude. As one level was zero, Part 1 provides a comparison between a rigid tool and one that is vibrating. In the analysis of variance (see Table 16) there is no interaction between blocks and replicates, or second-order interaction between the three factors, because the blocks are "nested" within the replicate. The model used for the analysis of variance was;

$$Y = M + T + B\underline{R} + TB + R + TR + \varepsilon$$

where Y is the observation,

M is the mean,

ε is the residual variance,

T, B and R are given in Table 16, and

$B\underline{R}$ is the notation that B is "nested" within R.

With the exception of the dense red soil, the treatments (amplitudes) were significant at the 5% level; that is, the draught of a vibrating tool is less than that of a rigid tool. Though this observation is largely a confirmation of work by other investigators, such as Eggenmüller (27), it has value in

Table 16. Draught of the Vertical Wedge (Part 1) - Statistical Analysis

Soil - Red/		Less Dense			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Treatments (T)	2	13217.27	6608.64	98.8*	74989.54	37494.77	10.5
Blocks (B)	2	166.89	83.45	1.2	130436.40	65218.20	18.2
TB	2	23.14	11.57	<1	2581.08	1290.54	<1
Replicates (R)	1	47.20	47.20	<1	39698.00	39698.00	11.1
TR	2	420.98	210.49	3.1	5000.32	2500.16	<1
Residual	2	133.75	66.88		7161.24	3580.62	
Total	11	14009.24			259866.60		

Duncan's Multiple Range

No. of Means	2	3		2	3	
LSR[1]	24.9	24.9		Not Applicable		
Treatments (λ)	∞	3	2	∞	3	2
Draught Means (lb)	141.6	91.8	61.1	543.1	376.2	374.6

Soil - Brown/		Less Dense			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Treatments (T)	2	11880.52	5940.26	65.4*	81704.11	40852.06	95.0*
Blocks	2	1719.16	859.58	9.5	23178.37	11589.19	26.9*
TB	2	686.32	343.16	3.8	730.36	365.18	<1
Replicates (R)	1	320.33	320.33	3.5	5275.21	5275.21	12.3
TR	2	227.30	113.65	1.3	8564.02	4282.01	10.0
Residual	2	181.54	90.77		860.40	430.20	
Total	11	15015.18			120312.49		

Duncan's Multiple Range

No. of Means	2	3		3	3	
LSR[1]	29.0	29.0		66.7	66.7	
Treatments (λ)	∞	3	2	∞	3	2
Draught Means (lb)	157.9	111.0	81.4	393.1	242.3	201.2

1. Protection level, 5%, * P < 5%

extending the observation to additional soils and densities.

In the less dense soils, the draught was a function of the amplitude, or was directly related to the magnitude of the dimensionless ratio, λ, if the frequency and travel rate are constant. For this density, the draught was significantly different for each amplitude. For the dense brown soil, only the draught for zero amplitude tested significantly different at the 5% level. It would appear from this that there is no advantage in using one amplitude over the other. This is not the case when the total horsepower (THP) is considered. This would also seem to be the case for the dense red soil. With additional observations, the draught for this soil and density might have tested significant.

Because there was little variation in the travel rate, it was unnecessary to analyse the DHP. The analyses would be similar to the draught. As for the input torque of the vibratory drive and the shaft horsepower (SHP), it is evident from inspection of the results that the difference between the dependent factors when the amplitude was zero, and when it was greater than zero, was significant. The torque and the SHP were consistently zero when the amplitude was zero, and were consistently greater than zero when the amplitude was greater than zero. What is of interest is the difference in the THP for the three levels of amplitude. Before calculating the analyses of variance, it was necessary to adjust the torque for friction in the drive and calculate the SHP before adding it to the DHP.

Adjustment for Drive Friction

From the conservation of energy;

$$\overline{t}_s = \overline{t} - t'$$

where $\overline{t}_s$ is the mean torque associated with tilling the soil,

$\overline{t}$ is the mean of the input torque to the vibratory drive,

and t' is the "frictional" torque.

The relationships of the above for Part 2 are illustrated in Figure 31. For the horizontal share (Part 2), the mean of the minimum frequency was used to estimate KA for each amplitude which, in turn, was used to calculate t' (equations 1 and 6, Chapter 6). These frequencies were 13.8 and 13.5 cps for the respective amplitudes of 0.010 and 0.020 ft. The basis for this choice is that it is only the increase in the amplitude from the minimum frequency that is of interest. The mean is specified so that, in determining the "load" torque, the variation about the mean is unaffected. For the vertical wedge, the choice of a "minimum frequency" is complicated because only the maximum frequency (nominally 37-1/2 cps) was used; that is, it was necessary to "select" a minimum frequency. The value chosen for the vertical wedge was 13.5 cps.

It is important to recognize that t' can be considered only an estimate of the drive friction. This is the implication of the somewhat arbitrary selections of the "minimum frequencies" made above. In addition, k (equation 3, Chapter 6) was assumed to be zero for these "minimum frequencies". Irrespective of the above, t' would still be an estimate because of variations that occurred in the state of the lubrication in the drive. There is one further complication.

In attempting to subtract t' from the individual observations of the torque (T), some values were so small that the results were negative. This was attributed to variations that occurred in the base frequency used to calculate T. The occurrences were largely limited to the minimum frequency (nominally 12-1/2 cps) in Part 2. In order to circumvent this difficulty, the adjustment

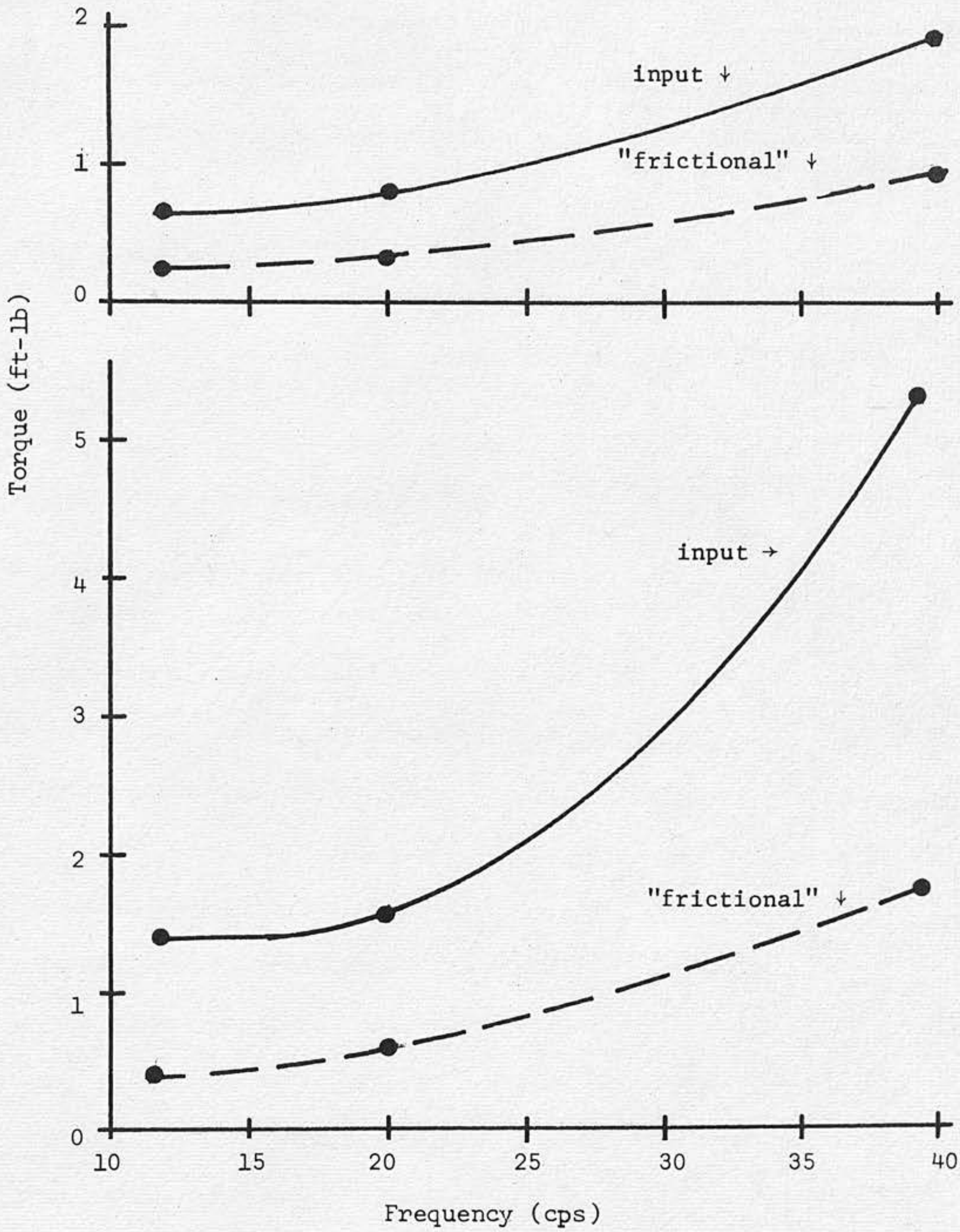


Figure 31 Input and "Frictional" Torque/Frequency Relationship (Part 2); top - minimum amplitude, btm - maximum amplitude.

for friction was made by multiplying T by $1 - t'/\bar{t}$. This factor was obtained by noting that the ratio of the "load" torque (T_s) to input torque (T) for an individual observation would be in the same proportion as the ratio for the mean of the "load" torque ($\bar{t}_s$) to the mean of the input torque ($\bar{t}$); that is,

$$T_s/T = \bar{t}_s/\bar{t} .$$

Substituting for $\bar{t}_s$,

$$T_s/T = \bar{t} - t'/\bar{t} \text{ , or}$$

$$T_s = T(1 - t'/\bar{t}).$$

This procedure has the added advantage in that the variability about the mean is unaffected. The pertinent values are given in Table 17.

Total Horsepower of the Vertical Wedge - Part 1

The heterogeneity of the residual variance for the THP (unadjusted) was not of the same order as it was for the draught. In view of this, separate analyses for only the two soils were required. The model used for the analysis of variance was;

$$Y = M + T + C + TC + R + TR + CR + TCR + B\underline{R} + TB + CB + TCB + \varepsilon$$

where Y, M and ε have been defined previously and the factors A, C, R and B are given in Table 18. The treatments (amplitude or dimensionless ratio, λ) and the densities were significant and, further, each treatment mean differed from one another. The relationship between the THP requirements of a rigid tool (λ of infinity) and a vibratory tool (λ of 2 or 3) is in agreement with the observation of Eggenmüller (27); that is, a vibrating tool is less efficient than a rigid one. It should be noted that this observation must be qualified because Part 1 was limited in scope and included only a vertical wedge.

Table 17: Drive Friction/Dimensionless Ratio, λ, Relationship

Part 1

λ	2	3
$\overline{f}$	35.3	39.6
$\overline{t}$	9.29	5.09
KA	0.001247	0.000713
t'	1.69	1.21
$1 - t'/\overline{t}$	0.818	0.761

Part 2

λ	1	2	3	2'	4	6
$\overline{f}$	38.6	20.0	13.5	39.7	20.2	13.8
$\overline{t}$	5.32	1.61	1.42	1.89	0.808	0.646
Without Springs						
KA		0.001080			0.000526	
t'	1.793	0.618	0.383	0.980	0.367	0.252
$1 - t'/\overline{t}$	0.663	0.614	0.729	0.481	0.546	0.610
With Springs						
KA		0.000999			0.000451	
t'	1.708	0.621	0.403	0.907	0.382	0.284
$1 - t'/\overline{t}$	0.680	0.613	0.715	0.520	0.527	0.560

Table 18: Total Horsepower of the Vertical Wedge (Part 1) - Statistical Analysis

Source of Variation	DF	Red Soil SS	Red Soil MS	Red Soil F	Brown Soil SS	Brown Soil MS	Brown Soil F
Treatments (T)	2	25.0404	12.5202	35.0***	22.2304	11.1152	129.2***
Densities (C)	1	25.3772	25.3772	70.9***	9.1934	9.1934	106.8***
TC	2	0.4697	0.2348	<1	0.0372	0.0186	<1
Replicates (R)	1	0.0556	0.0556	<1	0.3262	0.3262	3.8
TR	2	0.2132	0.1066	<1	0.9990	0.4995	5.8*
CR	1	1.9591	1.9591	5.5	0.6834	0.6834	7.9*
TCR	2	0.3128	0.1564	<1	0.0712	0.0356	<1
Blocks(B)	2	2.0838	1.0419	2.9	0.3153	0.1576	1.8
TB	2	0.1529	0.0764	<1	0.1001	0.0500	<1
CB	1	0.1364	0.1364	<1	0.0048	0.0048	<1
TCB	2	0.0180	0.0090	<1	0.4010	0.2005	2.3
Residual	5	1.7895	0.3579		0.4303	0.0861	
Total	23	57.6086			34.7921		

Duncan's Multiple Range

No. of Means	Red Soil 2		Red Soil 3	Brown Soil 2		Brown Soil 3
LSR*	0.770		0.791	0.378		0.388
Treatments (λ)	∞	3	2	∞	3	2
THP Means	1.571	2.772	4.109	1.394	2.693	3.748

* $P < 5\%$, *** $P < 0.5\%$

Draught and Drawbar Horsepower of the Horizontal Share

The analysis of variance of the draught and DHP for the horizontal share (Part 2) for each soil and density may be seen in Tables 19 and 20. The decision to regard blocks as a fixed effect is justified in that the blocks were significant except for the less dense red soil. A consistent main effect was the frequency. The only other main effect which was significant, was the plane of oscillation and that was limited to the brown soil. Of the first order interactions, the plane of oscillation and amplitude (H x A) response was consistent except for the less dense brown soil. A greater number of main effects and interactions were significant for the dense brown soil than for the dense red. This is largely attributed to the more variable response from the latter which in turn is attributed to the variation in the width of cut (see Chapter 6). The residual variance for the dense red soil was five to six times that for the other soil and densities. Because of the similarity in the response of the draught and the DHP, discussion of the one applies equally well to the other.

Frequency-Draught

The relationship between the draught and the frequency (and amplitude, plane of oscillation and rake angle) for the red soil is illustrated in Figures 32 to 35. The relationship for the brown soil is similar which may be noted from the data in the Appendix, Tables 9-11 to 9-15. The response in these figures (and tables) is not the simple effect. The values are the means which were "averaged over" the factor not stated, which is either the rake angle or the plane of oscillation. Only in the dense red soil (Figure 34) did the draught vary with the frequency and that was limited to the first two levels (12-1/2 and 18-3/4 cps). For the other level of frequency and for all the

Table 19: Draught of the Horizontal Share - Analysis of Variance

Soil - Red/		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	1681.6	152.8	1.7	43208.8	3928.1	6.2***
Frequency (F)	2	10551.9	5276.0	58.6***	27712.2	13856.1	21.8***
Rake Angle (R)	1	261.7	261.7	2.9	146.8	146.8	<1
Plane of Osc. (H)	1	27.8	27.8	<1	1014.0	1014.0	1.6
Amplitude (A)	1	302.5	302.5	3.4	43.9	43.9	<1
FR	2	4.4	2.2	<1	1202.6	601.3	<1
FH	2	281.9	140.9	1.6	916.7	458.4	<1
FA	2	73.6	36.8	<1	6690.3	3345.1	5.3**
RH	1	551.1	551.0	6.1*	173.1	173.1	<1
RA	1	65.6	65.6	<1	228.8	228.8	<1
HA	1	1088.1	1088.1	12.1***	5145.7	5145.7	8.1**
FRH	2	10.1	5.0	<1	445.8	222.9	<1
FRA	2	113.8	56.9	<1	468.5	234.3	<1
FHA	2	21.6	10.8	<1	1892.4	946.2	1.5
RHA	1	244.9	244.9	2.7	1327.8	1327.8	2.1
FRHA	2	8.2	4.1	<1	171.4	85.7	<1
Residual	37	3240.9	90.0		23553.9	636.6	
Total	71	18529.6			114342.6		

Cont'd.

* P < 5%, ** P < 1%, *** P < 0.5%

1 one observation missing

Table 19: Cont'd.

Soil - Brown/		Less Dense			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	8105.5	736.9	9.1***	11924.2	1084.0	7.9***
Frequency (F)	2	10895.3	5447.6	66.9***	17248.1	8624.0	62.8***
Rake Angle (R)	1	42.8	42.8	<1	394.8	394.8	2.9
Plane of Osc. (H)	1	2453.5	2453.5	30.2***	3010.9	3010.9	21.9***
Amplitude (A)	1	156.9	156.9	1.9	3.4	3.4	<1
FR	2	112.6	56.3	<1	25.2	12.6	<1
FH	2	246.1	123.0	1.5	947.5	473.8	3.4*
FA	2	499.4	249.7	3.1	1996.3	998.2	7.3***
RH	1	170.7	170.7	2.1	2147.6	2147.6	15.6***
RA	1	413.8	413.8	5.1*	511.9	511.9	3.7
HA	1	590.9	590.9	7.3*	1436.4	1436.4	10.5***
FRH	2	170.6	85.3	1.0	297.6	148.8	1.1
FRA	2	702.1	351.0	4.3*	599.5	299.7	2.2
FHA	2	139.4	69.7	<1	455.3	227.7	1.7
RHA	1	230.8	230.8	2.8	534.6	534.6	3.9
FRHA	2	162.0	81.0	<1	1389.6	694.8	5.1*
Residual	37	3010.9	81.4		5082.6	137.4	
Total	71	28103.4			48005.5		

* P < 5%, *** P < 0.5%

Table 20: Drawbar Horsepower of the Horizontal Share - Analysis of Variance

Soil - Red/		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	0.01380	0.00125	1.6	0.34881	0.03171	6.2***
Frequency (F)	2	0.08847	0.04423	54.9***	0.25151	0.12575	24.7***
Rake Angle (R)	1	0.00268	0.00268	3.3	0.00098	0.00098	<1
Plane of Osc. (H)	1	0.00018	0.00018	<1	0.00740	0.00740	1.5
Amplitude (A)	1	0.00290	0.00290	3.6	0.00229	0.00229	<1
FR	2	0.00003	0.00002	<1	0.01359	0.00680	1.3
FH	2	0.00190	0.00095	1.2	0.00682	0.00340	<1
FA	2	0.00016	0.00008	<1	0.06250	0.03125	6.1**
RH	1	0.00476	0.00476	5.9*	0.00186	0.00186	<1
FA	1	0.00048	0.00048	<1	0.00150	0.00150	<1
HA	1	0.00860	0.00860	10.7***	0.04257	0.04257	8.4**
FRH	2	0.00014	0.00007	<1	0.00377	0.00189	<1
FRA	2	0.00065	0.00032	<1	0.00272	0.00136	<1
FHA	2	0.00009	0.00004	<1	0.01320	0.00660	1.3
RHA	1	0.00244	0.00244	3.0	0.01150	0.01150	2.3
FRHA	2	0.00010	0.00005	<1	0.00132	0.00066	<1
Residual	37	0.02900	0.00081		0.18850	0.00510	
Total	71	0.15639			0.96085		

* P < 5%, ** P < 1%, *** P < 0.5%

1 one observation missing

Table 20: Cont'd.

Soil - Brown/		Less Dense			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	0.08193	0.00744	8.7**	0.09803	0.00891	8.2***
Frequency (F)	2	0.09574	0.04787	55.9***	0.15468	0.07734	71.0***
Rake Angle (R)	1	0.00002	0.00001	<1	0.00289	0.00289	2.7
Plane of Osc. (H)	1	0.02612	0.02612	30.5***	0.02645	0.02645	24.3***
Amplitude (A)	1	0.00045	0.00045	<1	0.00021	0.00021	<1
FR	2	0.00057	0.00028	<1	0.00024	0.00012	<1
FH	2	0.00408	0.00204	2.4	0.00740	0.00370	3.4*
FA	2	0.00174	0.00087	1.0	0.01678	0.00839	7.7***
RH	1	0.00160	0.00160	1.9	0.01660	0.01660	15.2***
RA	1	0.00478	0.00478	5.6*	0.00471	0.00471	4.3*
HA	1	0.00192	0.00192	2.2	0.01106	0.01106	10.2***
FRH	2	0.00351	0.00176	2.1	0.00292	0.00146	1.4
FRA	2	0.00536	0.00268	3.1	0.00460	0.00230	2.1
FHA	2	0.00074	0.00037	<1	0.00286	0.00143	1.3
RHA	1	0.00059	0.00059	<1	0.00436	0.00436	4.0*
FRHA	2	0.00209	0.00104	1.2	0.01107	0.00553	5.1*
Residual	37	0.03166	0.00086		0.04031	0.00109	
Total	71	0.26292			0.40517		

* $P < 5\%$, *** $P < 0.5\%$

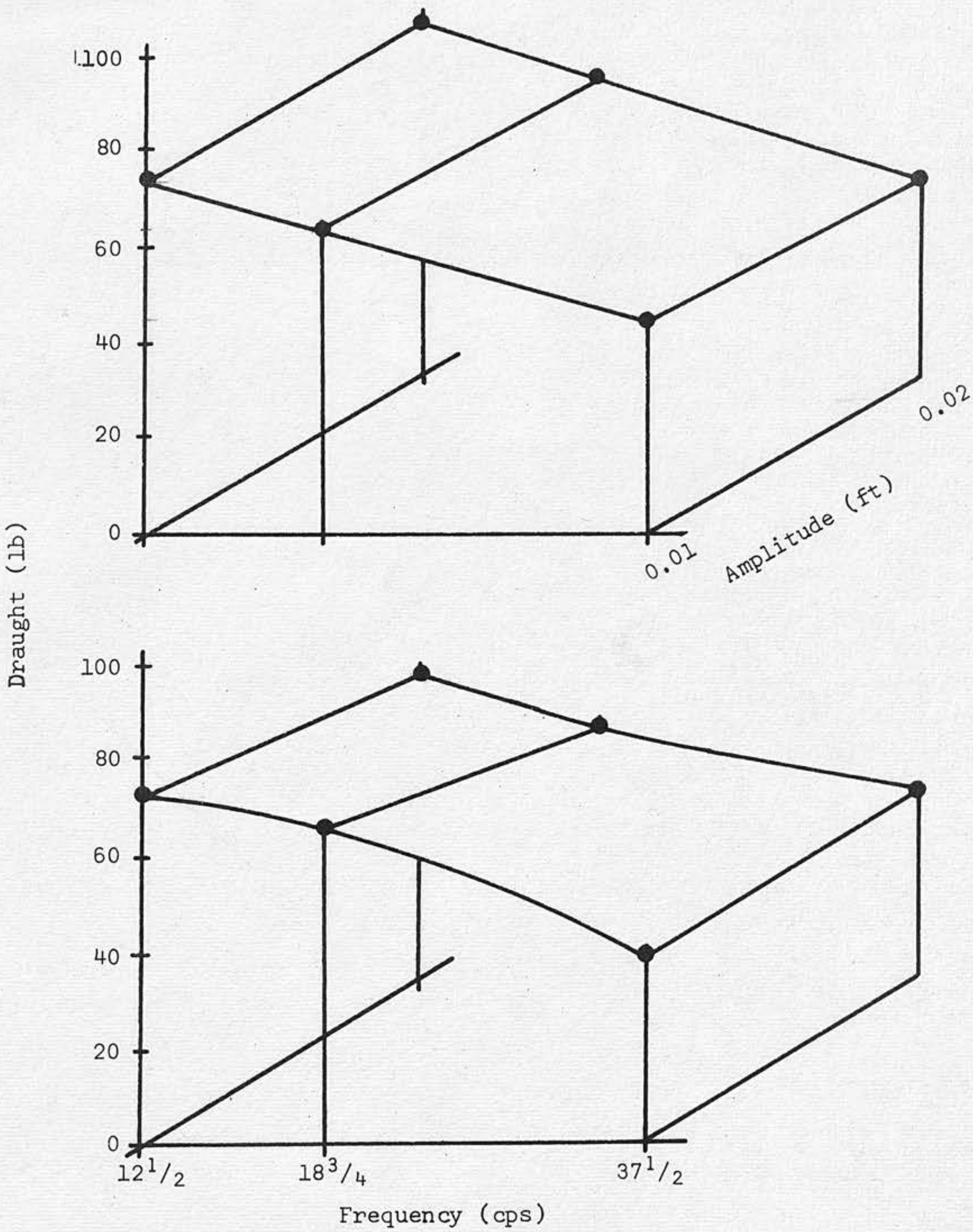


Figure 32 Draught of the Horizontal Share for the Less Dense Red Soil; top - horizontal plane of oscillation, btm - tilted.

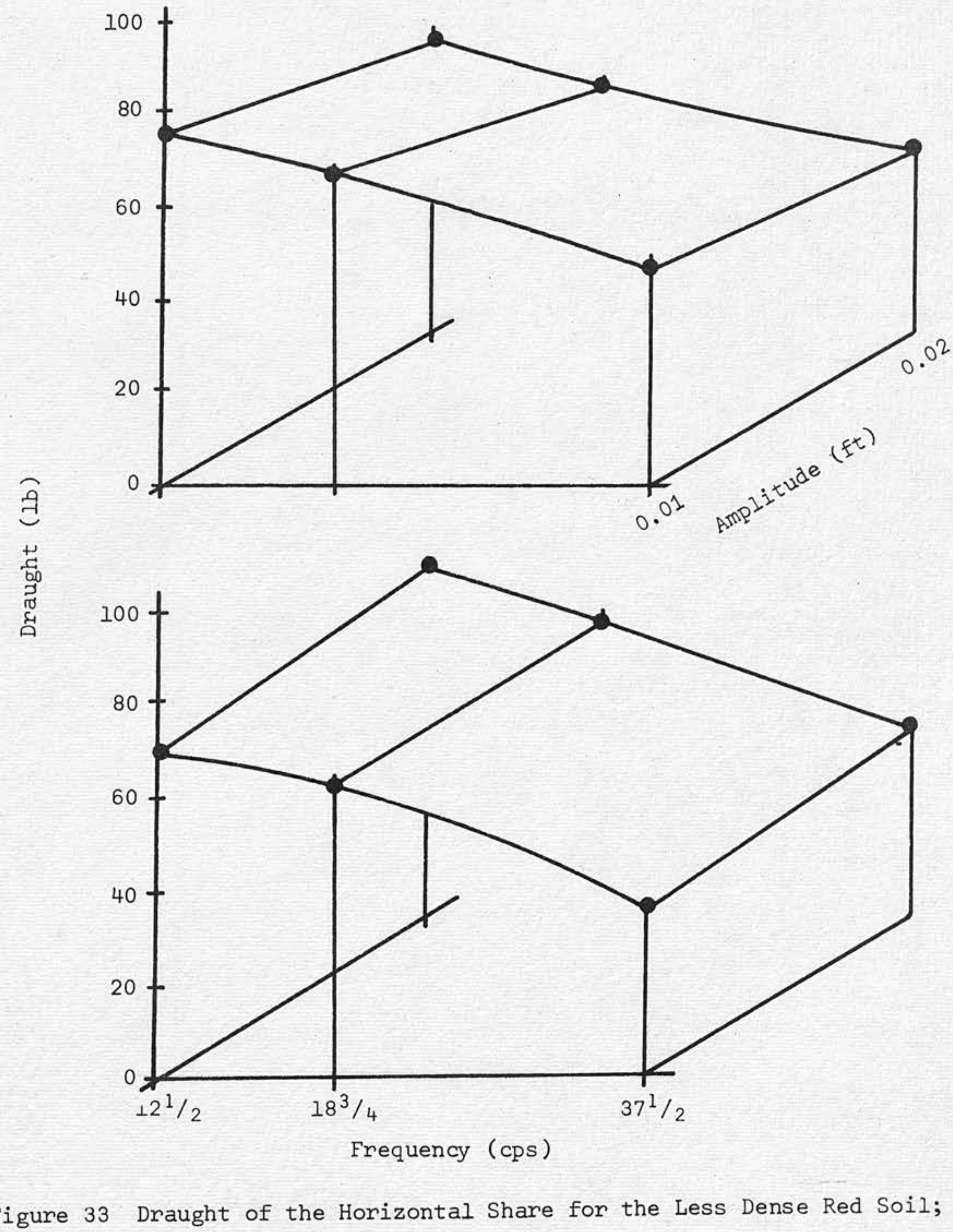


Figure 33 Draught of the Horizontal Share for the Less Dense Red Soil; top - zero rake angle, btm - 20°.

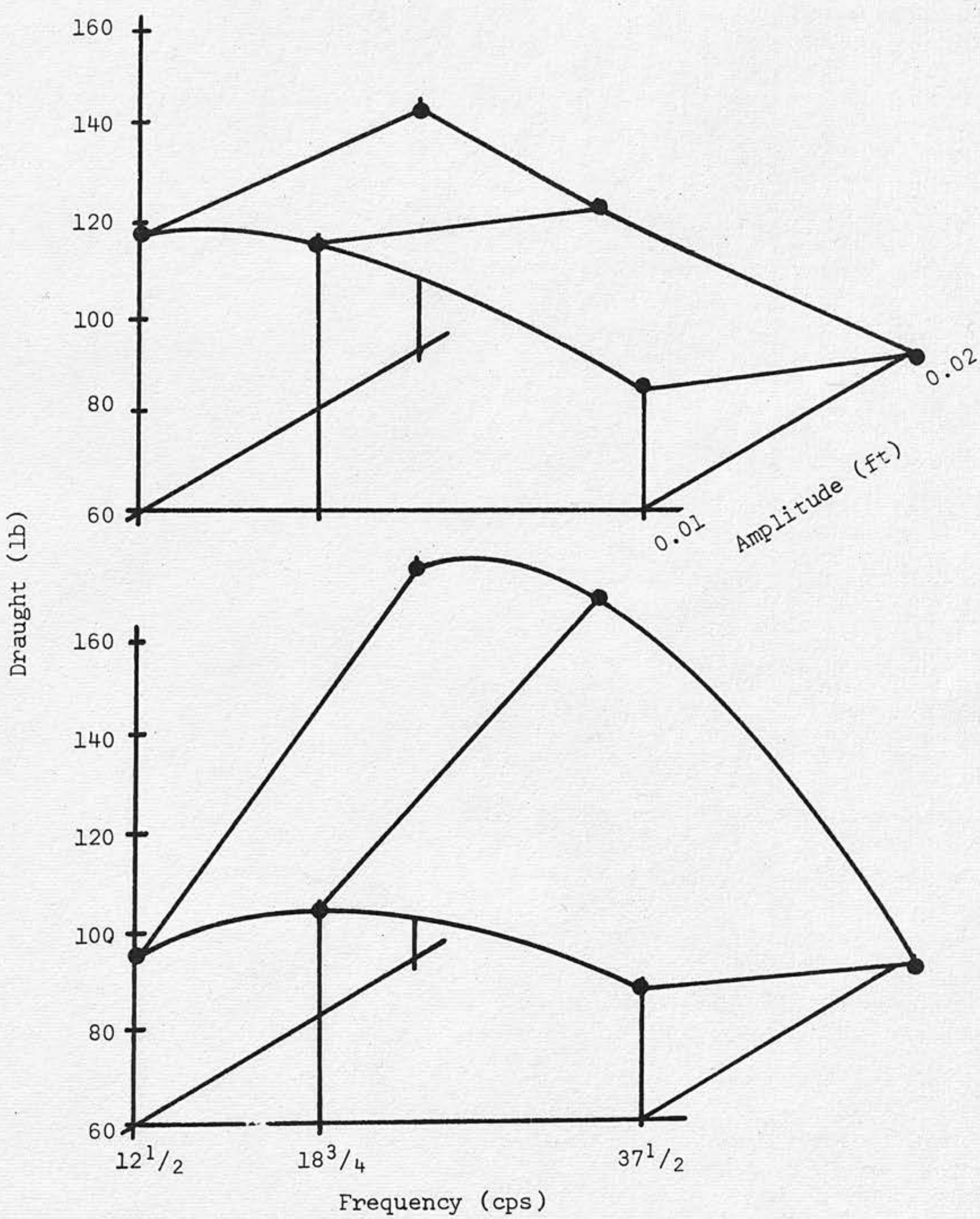


Figure 34 Draught of the Horizontal Share for the Dense Red Soil; top - horizontal plane of oscillation, btm - tilted.

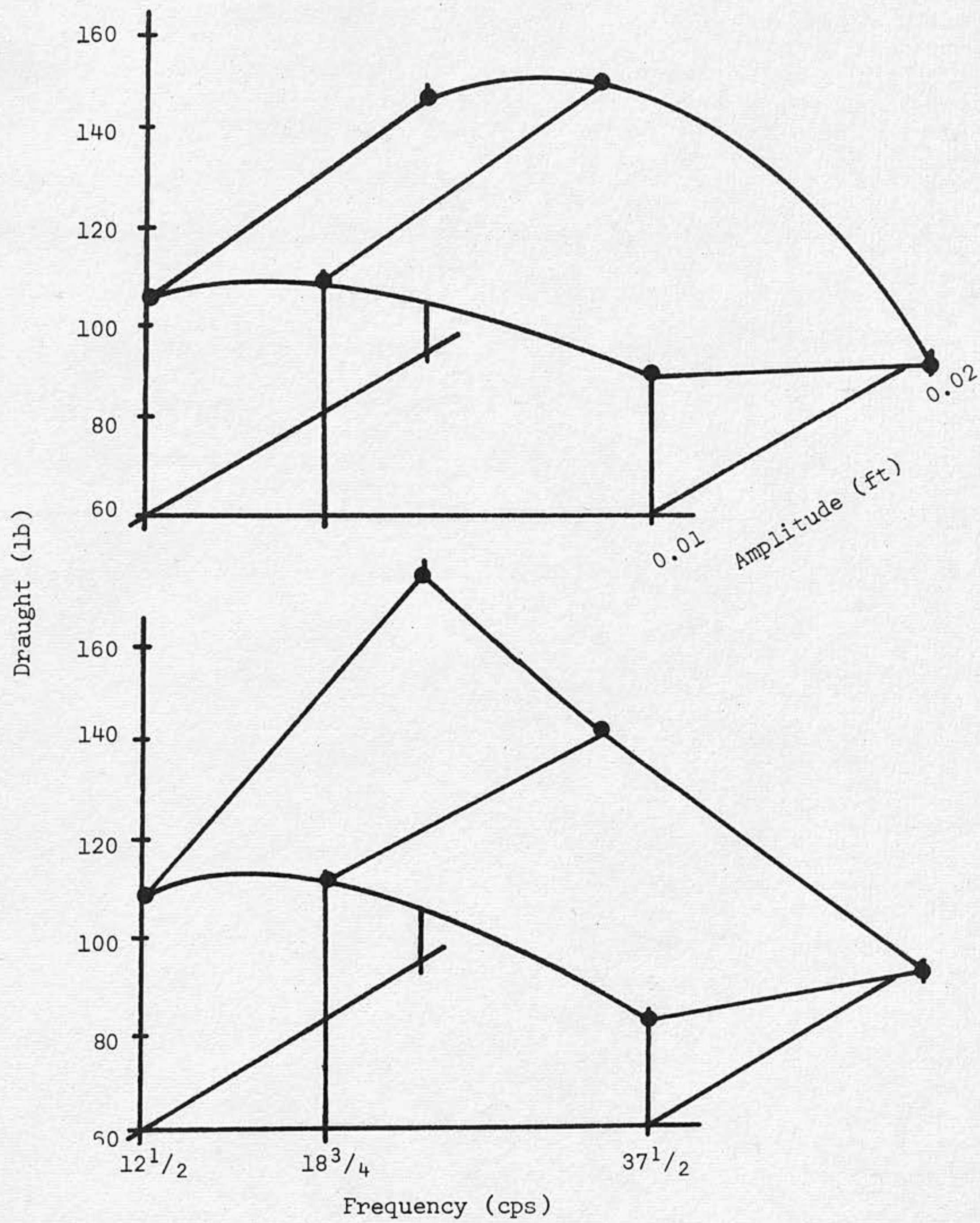


Figure 35 Draught of the Horizontal Share for the Dense Red Soil; top - zero rake angle, btm - 20°.

other factors and their levels (including the brown soil), the draught varied inversely with the frequency. It follows from this that the draught (and DHP) is a function of the dimensionless ratio, λ, if the amplitude and travel rate are constant. This observation agrees with the conclusions of other investigators such as Eggenmüller (27) and Gunn and Tramontini (39). It is worthwhile to note that the regression coefficients (linear) of the draught-frequency relationships were found to be homogeneous for those comparisons that exhibited common variances (Table 21); that is, the relationship between the draught and the frequency is the same for the less dense red, less dense brown and the dense brown soils. Two of the three comparisons between these soils and the dense red are heterogeneous but the comparisons are invalid because the variance of the dense red soil was substantially larger than the other three.

Table 21: Comparisons of the Draught-Frequency Regression Coefficients (t-test)

```
Less Dense Red  →   0.03   ←  Less Dense Brown
       → 1.48           (2.08*) ←
    ↓                                ↓
 (2.06*)                            1.54
    ↑                                ↑
       → (2.08*)          1.48   ←
     Dense Red  →  (1.18)  ←  Dense Brown
```

*P < 5%

Amplitude and Amplitude-Frequency Interaction - Draught

It is evident from the analysis of variance that the amplitude is not independent of the frequency in the dense soils. This is indicated by the significant first order interactions of amplitude and frequency. There is, in effect, a change in the response due to amplitude depending on the level of frequency. The absence of a significant main effect of amplitude indicates that the change in response is more than a matter of degree (see Figures 37 and 39 - btm). At the maximum frequency (37-1/2 cps), the draught response agrees with the concept that the draught is a function of λ where λ is inversely related to the amplitude for constant frequency and travel rate. At 18-3/4 cps, the draught is essentially the same for either amplitude; that is, the draught is not a function of λ. At the minimum frequency (12-1/2 cps), the draught is directly related to the amplitude, this relationship being opposite to the response obtained at the maximum frequency. The differential response of the draught for the amplitude and frequency may also be seen by noting the "warpage" of the response surfaces in Figures 34 and 35.

Barkan (7) declares that there is a minimum or critical amplitude of vibration. The response obtained for the amplitude in the dense soils suggests something in addition to this observation. There appears to be an optimum amplitude which is dependent on the level of frequency. In the less dense soils there is neither a critical nor an optimum amplitude, at least not within the range of the two amplitudes used in the experimental work.

In the dense brown soil there was a plane of oscillation-frequency interaction but it was significant only at the 5% level (Figure 40 btm). On the other hand the plane of oscillation-amplitude interaction was highly significant for this soil and density and for the red soil at both densities.

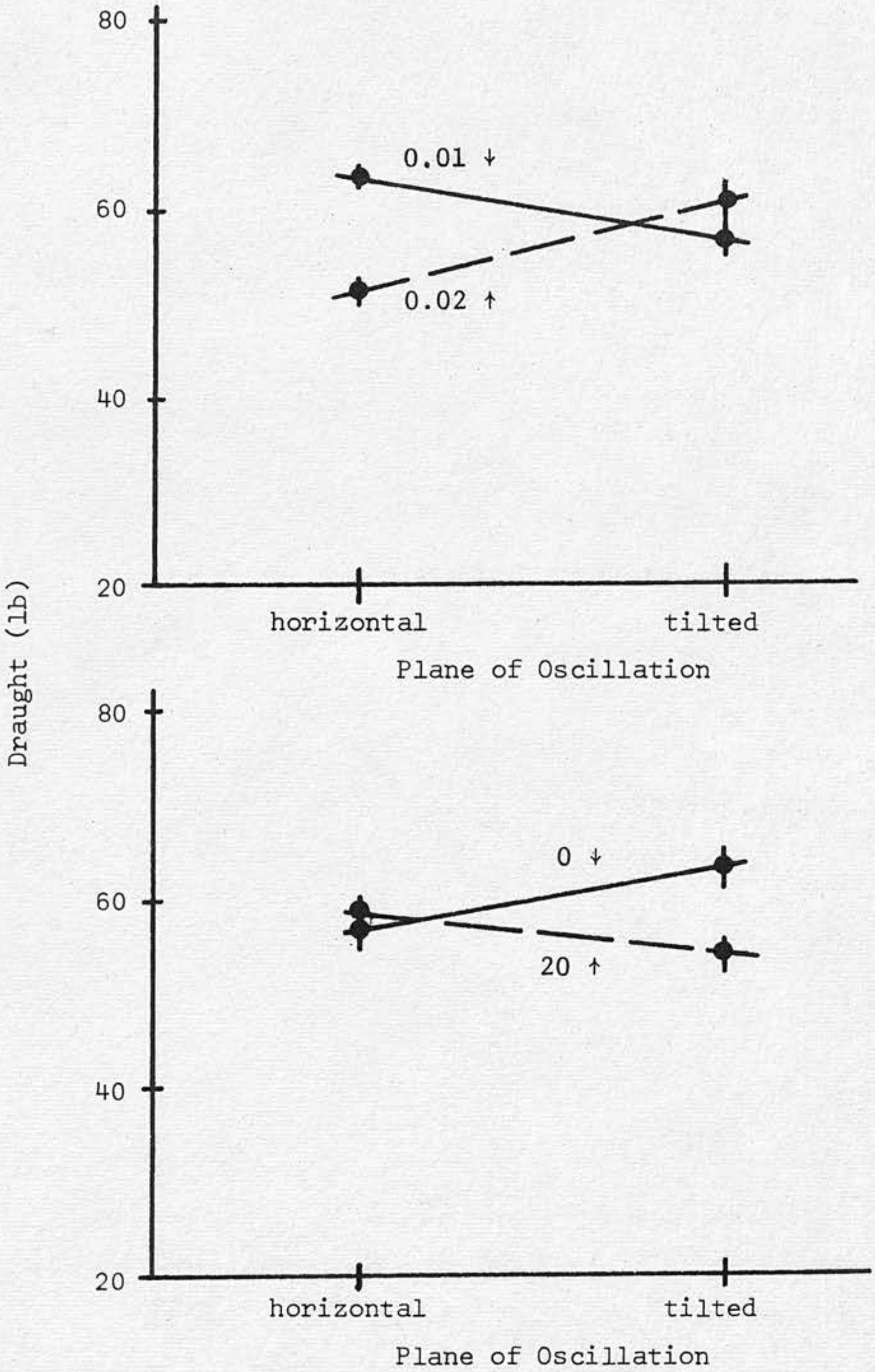


Figure 36 Significant Draught Interactions (first-order) in the Less Dense Red Soil; top - amplitude (ft), btm - rake angle (^{o}).

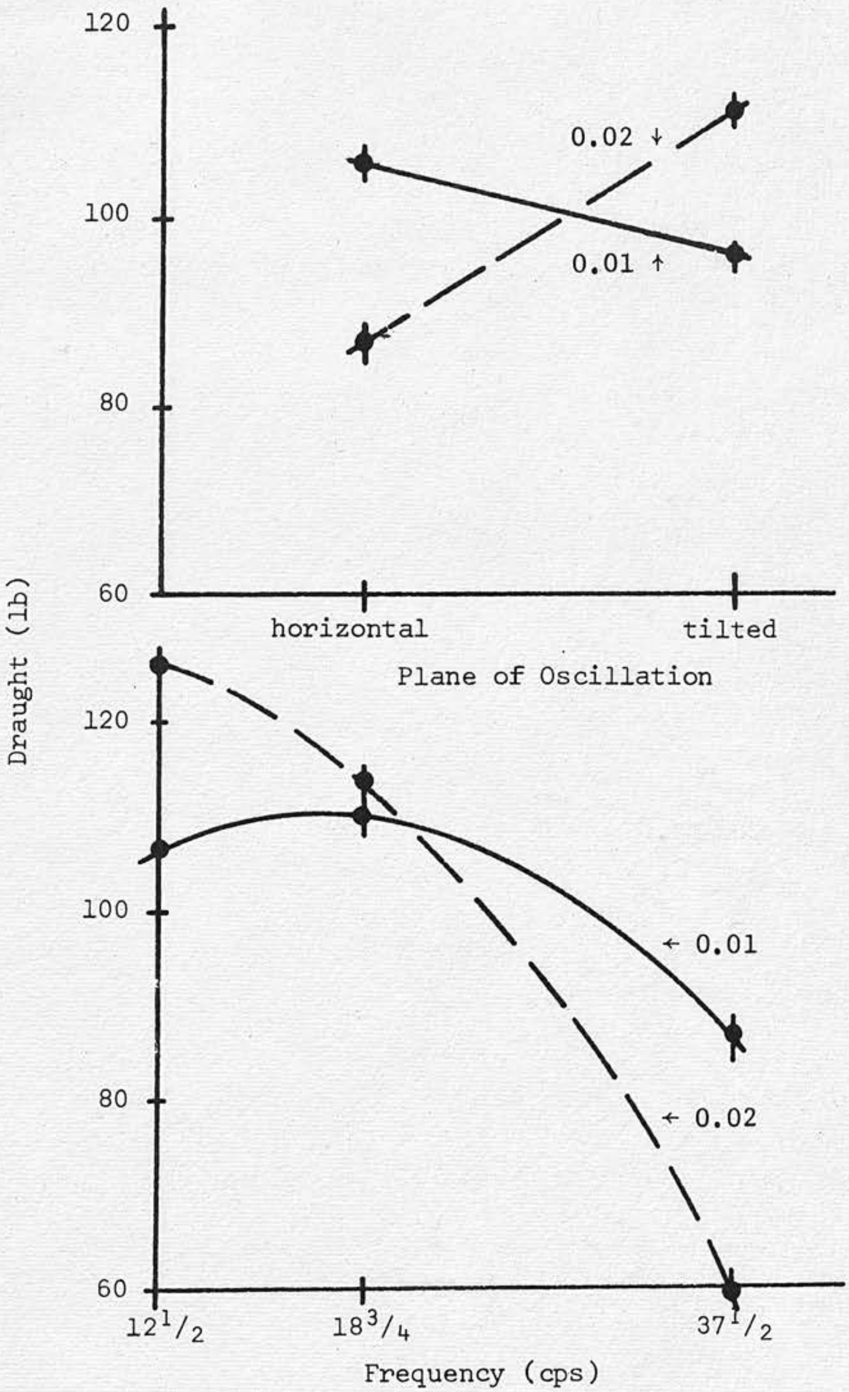


Figure 37 Significant Draught Interactions (first-order) in the Dense Red Soil; top and btm - amplitude (ft).

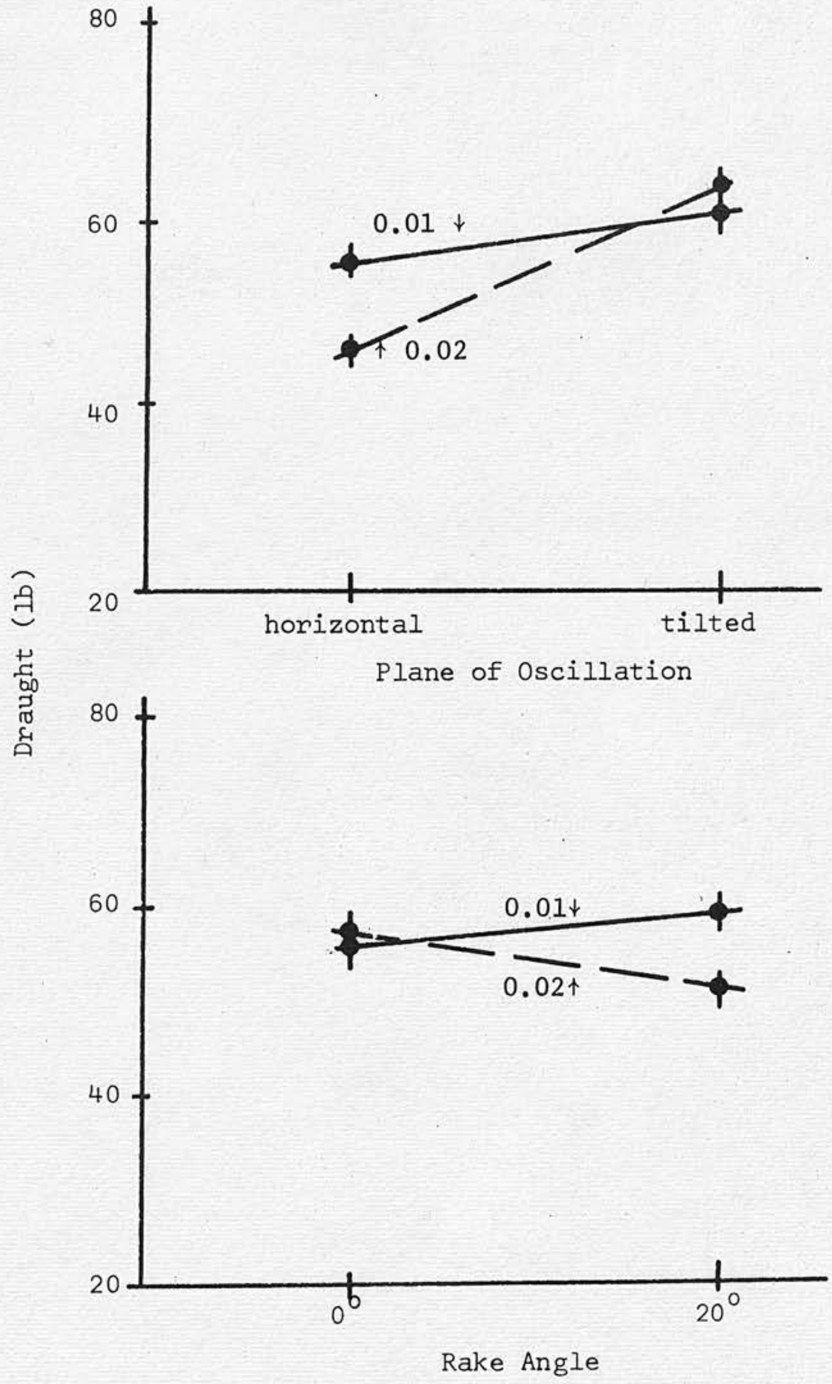


Figure 38 Significant Draught Interactions (first-order) in the Less Dense Brown Soil; top and btm - amplitude (ft).

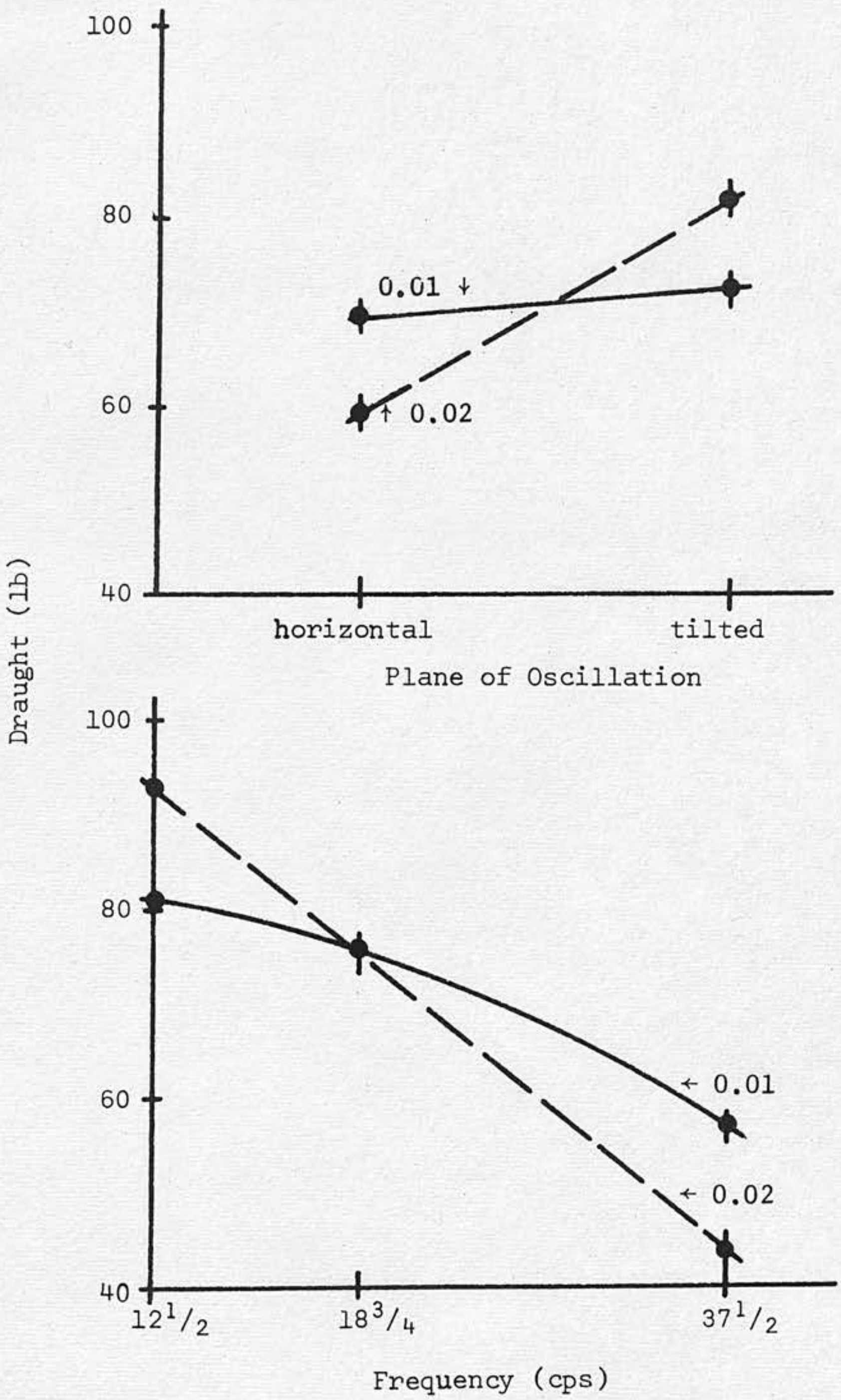


Figure 39 Significant Draught Interactions (first-order) in the Dense Brown Soil; top and btm - amplitude (ft).

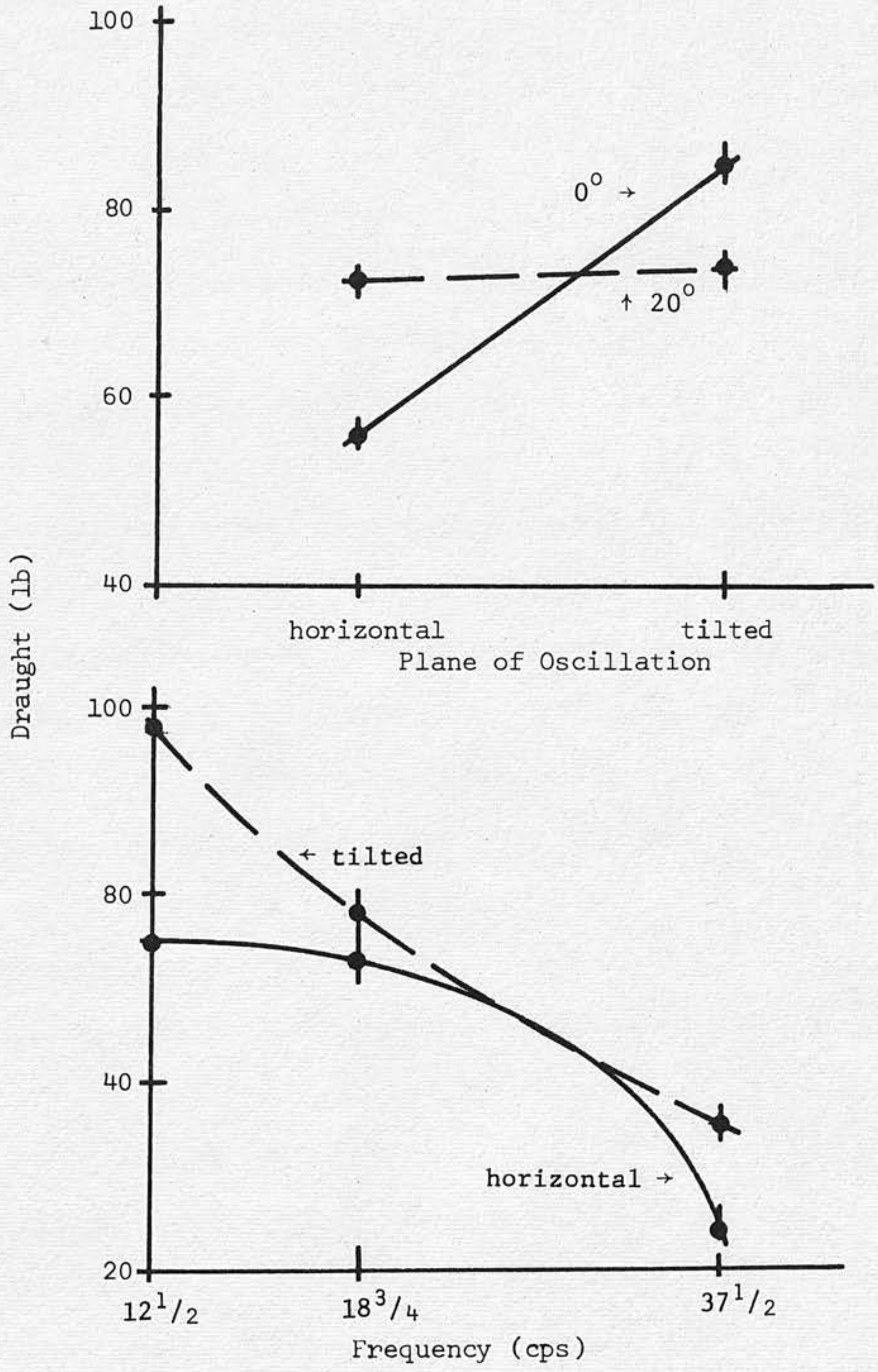


Figure 40 Significant Draught Interactions (first-order) in the Dense Brown Soil; top - rake angle (°), btm - plane of oscillation.

This interaction is noted in the following section.

Plane of Oscillation and the Plane-Amplitude Interaction - Draught

In the brown soil, there was an increase in the draught when the plane of oscillation was tilted out of the horizontal (main effect). There was also a differential response (interaction) with respect to the amplitude but the trend was the same for both density levels (see Figures 38 and 39 top). The relationship between the draught and the plane of oscillation, however, is the opposite to that obtained by Eggenmüller (27).

In the red soil, the relationship is more complex. The absence of a significant main effect is primarily the result of the change in response for the two levels of amplitude (see Figures 36 and 37, top). There was an increase in the draught when the plane of oscillation was tilted for the maximum level of amplitude, this being in agreement with that obtained for the brown soil. For the minimum amplitude, however, there was a decrease in the draught, this decrease being in agreement with Eggenmüller's findings. This differential response of the draught, excluding the maximum frequency, is readily seen in Figure 34.

Eggenmüller (27) proposes that the draught of a vibratory tool is reduced for a tilted plane of oscillation because the friction between the tool and the soil flowing over it is reduced and because the rake angle is reduced during the cutting phase. He states that the friction and the cutting angle are a function of the plane of oscillation, frequency, amplitude, travel rate and the rake angle. It would appear that the friction and the cutting resistance may be a function of the soil type and density as well. At least this may account for some of the difference between the results of the experimental work and that obtained by Eggenmüller (27). It is evident that

Eggenmüller (27) did not use a factorial experiment and may have been unaware of a plane of oscillation-amplitude interaction. A contributing cause of the difference was friction on the underside of the share when the rake angle was zero and the plane of oscillation was tilted. The effect is noted in the next section.

Rake Angle Interactions - Draught

The draught response for the rake angle is limited in spite of the marked difference in the soil tilth when the rake angle was changed (compare Plates 10 and 12, 11 and 13, etc.). This suggests that either the additional strain to cause soil pulverization does not incur much, if any, draught penalty, or that a cutter with practical dimensions causes soil fracture which cannot be readily observed. If the latter is valid, then the function of the rake angle is largely the displacement of the broken soil blocks or clods.

There are some significant interactions of the rake angle with respect to the amplitude and the plane of oscillation. Only the rake angle-plane of oscillation interaction is highly significant and that occurred only in the dense brown soil (Figure 40 top). The trend, however, is similar to the interaction in the less dense red soil (Figure 36 btm). There is little or no change in draught when the plane of oscillation is tilted when the rake angle is 20°, but it increases if the rake angle is zero. The latter is attributed to friction occurring on the bottom side of the share as the share moves downward in the soil. In using a zero rake angle for both planes of oscillation, Eggenmüller's warning (27) was ignored. The dilemma was either to avoid a zero rake angle and, therefore, an estimate of cutting versus cutting and pulverization (for the horizontal plane of oscillation) or to include a zero rake angle and expect some friction on the underside of the tool when the plane of oscillation was tilted. Friction from this source for the 20° rake angle was not likely because it exceeded the maximum downward angle (except λ of 2') of the tool velocity vector (see Figure 29). In view of this, the prior observation that there was little or no reduction in the draught for the tilted plane of oscillation is not nullified.

The rake angle-amplitude interaction in the less dense brown soil and the two second-order[1] and the one third-order interactions were significant only at the 5% probability level and did not occur for the other soils and densities. Under these circumstances any conclusion drawn from these interactions would be limited and not on a firm basis. In view of this, no discussion of them has been attempted.

Torque and Shaft Horsepower of the Horizontal Share

The analysis of variance of the torque and SHP for the horizontal share for each soil and density may be seen in Tables 22 and 23. The blocks were not significant, which was unlike the response obtained for the draught and DHP. This suggests that the torque and SHP are independent of the soil density. The only consistent main effects (significant) were the frequency and amplitude. The main effects of the rake angle and plane of oscillation were significant only for the SHP and they were limited to the less dense brown soil for the rake angle and to the dense red soil for the plane of oscillation. Because of the similarity in the response of the torque and SHP, discussion of one will suffice for the other.

Frequency and Amplitude - Torque

The torque-frequency and the torque-amplitude relationships for

1 Some loss of precision, due to confounding, occurred for the second-order interaction in the less dense brown soil.

Table 22: Torque of the Horizontal Share - Analysis of Variance

Soil - Red		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	2.8769	0.2615	3.2**	1.3563	0.1233	<1
Frequency (F)	2	44.9927	22.4964	272.1***	28.6469	14.3234	94.8***
Rake Angle (R)	1	0.1372	0.1372	1.7	0.2356	0.2356	1.6
Plane of Osc. (H)	1	0.0250	0.0251	<1	0.5990	0.5990	4.0
Amplitude (A)	1	27.0766	27.0766	327.4***	31.2590	31.2590	206.9***
FR	2	0.4899	0.2449	3.0	0.1116	0.0558	<1
FH	2	0.0904	0.0452	<1	1.5105	0.7552	5.0*
FA	2	17.5252	8.7626	106.0***	13.7883	6.8941	46.2***
RH	1	0.0698	0.0698	<1	0.0672	0.0672	<1
RA	1	0.9420	0.9420	11.4***	0.0270	0.0270	<1
HA	1	0.5149	0.5149	6.2*	0.0127	0.0127	<1
FRH	2	0.0947	0.0473	<1	0.1912	0.0956	<1
FRA	2	0.7662	0.03831	4.6*	0.0223	0.0111	<1
FHA	2	0.0800	0.0400	<1	0.08759	0.4380	2.9
RHA	1	0.1169	0.1169	1.4	0.0128	0.0128	<1
FRHA	2	0.1049	0.0525	<1	0.1402	0.0701	<1
Residual	37	2.9768	0.0827		5.5905	0.1510	
Total	71	98.8803			84.4469		

* P < 5%, ** P < 1%, *** P < 0.5%

1 - one observation missing

Table 22: Cont'd.

Soil - Brown/		Less Dense			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	1.3911	0.1265	2.2*	2.8959	0.2633	2.0
Frequency (F)	2	43.6007	21.8004	372.3***	41.6914	20.8457	162.1***
Rake Angle (R)	1	0.0731	0.0731	1.3	0.0255	0.0255	<1
Plane of Osc. (H)	1	0.1733	0.1733	3.0	0.0016	0.0016	<1
Amplitude (A)	1	27.5752	27.5752	471.0***	29.7979	29.7979	231.7***
FR	2	0.3910	0.1955	3.3*	0.4135	0.2067	1.6
FH	2	0.1174	0.0587	1.0	1.1180	1.5600	4.4*
FA	2	14.5757	7.2879	124.5***	19.3652	9.6826	75.3***
RH	1	0.1969	0.1969	3.4	0.2057	0.2057	1.6
RA	1	0.0012	0.0012	<1	0.1447	0.1447	1.1
HA	1	0.3904	0.3904	6.7*	0.4003	0.4003	3.1
FRH	2	0.0410	0.0205	<1	0.4911	0.2455	1.9
FRA	2	0.0061	0.0030	<1	0.3692	0.1846	1.4
FHA	2	0.3308	0.1654	2.8	0.2520	0.1262	<1
RHA	1	0.0768	0.0768	1.3	0.0210	0.0210	<1
FRHA	2	0.0711	0.0356	<1	1.6917	0.8458	6.6***
Residual	37	2.1662	0.0586		4.7582	0.1286	
Total	71	91.1780			103.6453		

* P < 5%, *** P < 0.5%

Table 23: Shaft Horsepower of the Horizontal Share - Analysis of Variance

Soil - Red/		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	0.49820	0.04529	5.3***	0.14318	0.01302	<1
Frequency (F)	2	12.71818	6.35909	42.2***	10.30168	5.15084	392.5***
Rake Angle (R)	1	0.02161	0.02161	2.5	0.00756	0.00756	<1
Plane of Osc. (H)	1	0.00187	0.00187	<1	0.11440	0.11440	8.7**
Amplitude (A)	1	3.34781	3.34781	40.8***	3.90601	3.90601	297.6***
FR	2	0.04483	0.02241	2.6	0.00160	0.00080	<1
FH	2	0.00938	0.00469	<1	0.25768	0.12884	9.8***
FA	2	4.12438	2.06219	239.6***	4.05233	2.02617	154.4***
RH	1	0.00285	0.00285	<1	0.00114	0.00114	<1
RA	1	0.11893	0.11893	14.0***	0.00055	0.00055	<1
HA	1	0.03727	0.03727	4.4*	0.01163	0.01163	<1
FRH	2	0.01376	0.00688	<1	0.01845	0.00922	<1
FRA	2	0.01252	0.05126	6.0**	0.00023	0.00011	<1
FHA	2	0.01394	0.00697	<1	0.09797	0.04898	3.7*
RHA	1	0.01356	0.01356	1.6	0.00068	0.00068	<1
FRHA	2	0.01750	0.00875	1.0	0.00832	0.00416	<1
Residual	37	0.30663	0.00852		0.48555	0.01312	
Total	71	21.39324			19.40897		

* P < 5%, ** P < 1%, *** P < 0.5%

1 - one observation missing

Table 23: Cont'd.

Soil - Brown/		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	0.11737	0.01067	1.6	0.28360	0.02578	1.4
Frequency (F)	2	13.02334	6.51167	954.5***	12.55665	6.27832	330.0***
Rake Angle (R)	1	0.04076	0.04076	6.0*	0.00477	0.00477	<1
Plane of Osc. (H)	1	0.01523	0.01523	2.2	0.01140	0.01140	<1
Amplitude (A)	1	3.15786	3.15786	462.9***	4.04701	4.04701	212.7***
FR	2	0.06472	0.03236	4.7*	0.03921	0.01961	1.0
FH	2	0.00043	0.00022	<1	0.08619	0.04310	2.3
FA	2	3.56542	1.78271	261.3***	4.95933	2.47967	130.4***
RH	1	0.01811	0.01811	2.7	0.00261	0.00261	<1
RA	1	0.00442	0.00442	<1	0.01134	0.01134	<1
HA	1	0.02750	0.02750	4.0	0.00842	0.00842	<1
FRH	2	0.02589	0.01294	1.9	0.08517	0.04258	2.2
FRA	2	0.00364	0.00182	<1	0.04607	0.02303	1.2
FHA	2	0.02803	0.01401	2.1	0.00609	0.00305	<1
RHA	1	0.00214	0.00214	<1	0.00966	0.00966	<1
FRHA	2	0.00147	0.00073	<1	0.12967	0.06483	3.4*
Residual	37	0.24560	0.00682		0.70383	0.01902	
Total	71	20.34192			22.99103		

* $P < 5\%$, *** $P < 0.5\%$

1 - one observation missing

the red soil are illustrated in Figures 41 and 42. As was the case for the draught, the responses in these figures are not the simple effects. The relationships for the brown soil (and rake angle) are not illustrated because they are so similar to that obtained for the red soil. This may be noted from the data in the Appendix, Tables 9-13 and 9-14. The torque is directly related to the amplitude (Figures 41 and 42) and also to the two upper levels of the frequency. The torque response is significant as indicated by the analysis of variance (main effects). It is evident from the "warpage" of the response surfaces that the frequency is not independent of the amplitude; that is, there is a frequency-amplitude interaction.

<u>Interactions - Torque</u>

The frequency-amplitude interaction (Figures 43 to 45) is significant for both soils and densities. The differential response is attributed to the exceedingly large torque requirements at the maximum frequency-maximum amplitude combination (λ of 1) which is associated with reversal of the tool in the soil. This observation is in agreement with the results obtained by Eggenmüller (27).

Figure 43-btm (rake angle-amplitude interaction) indicates that the 20° rake angle required more torque than the 0° rake angle for the minimum amplitude, but the reverse for the maximum. This interaction, however, is significant only for the less dense brown soil. The plane of oscillation-frequency interaction is significant for the dense red and brown soils (illustrated only for the dense red soil, Figure 44-btm). The tilted plane of oscillation required less torque than the horizontal, but only at the maximum frequency. The other significant first and second-order interactions were significant only at the 5% probability level. With the exception of the

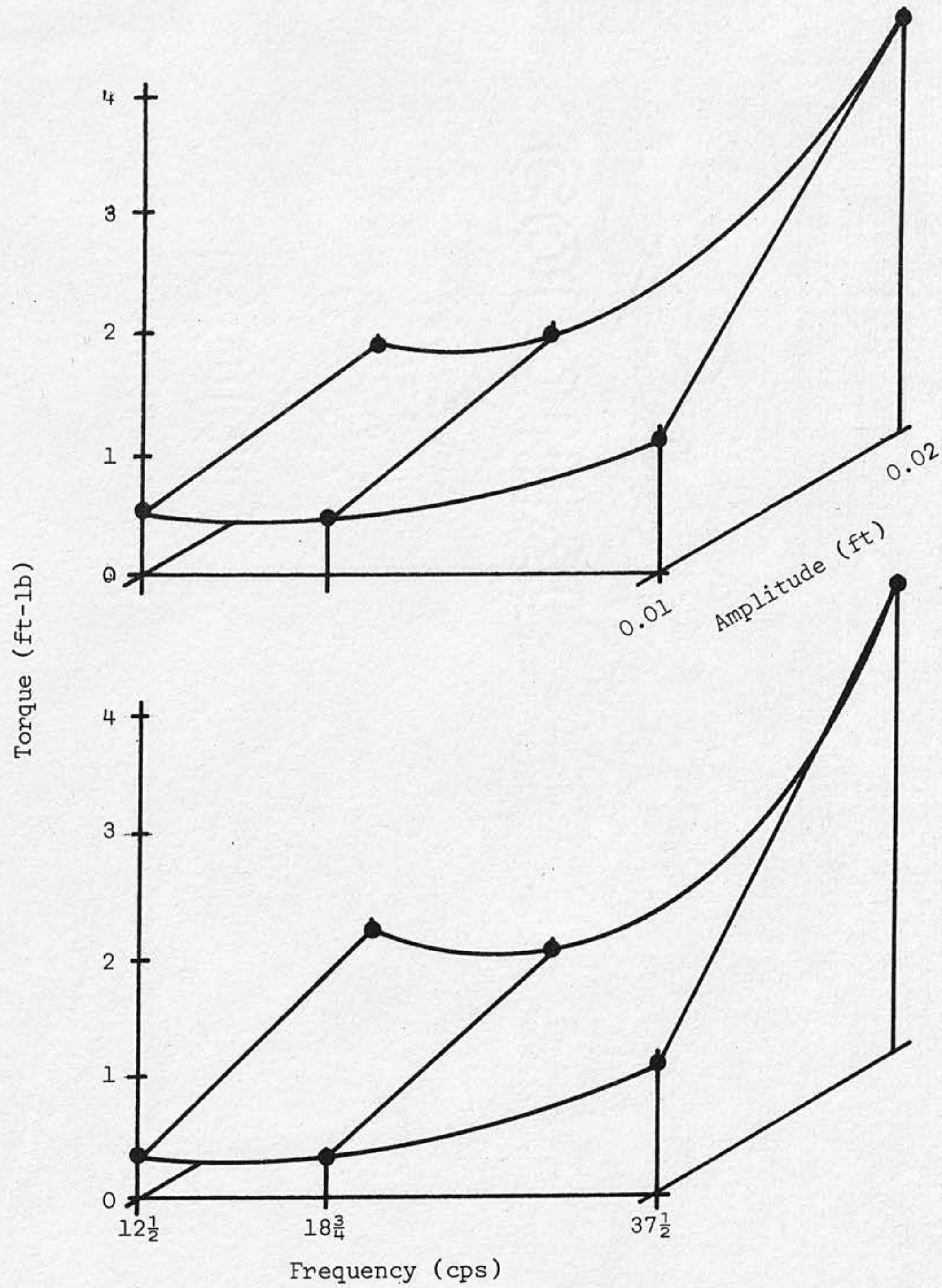


Figure 41 Torque of the Horizontal Share for the Less Dense Red Soil; top - horizontal plane of oscillation, btm - tilted.

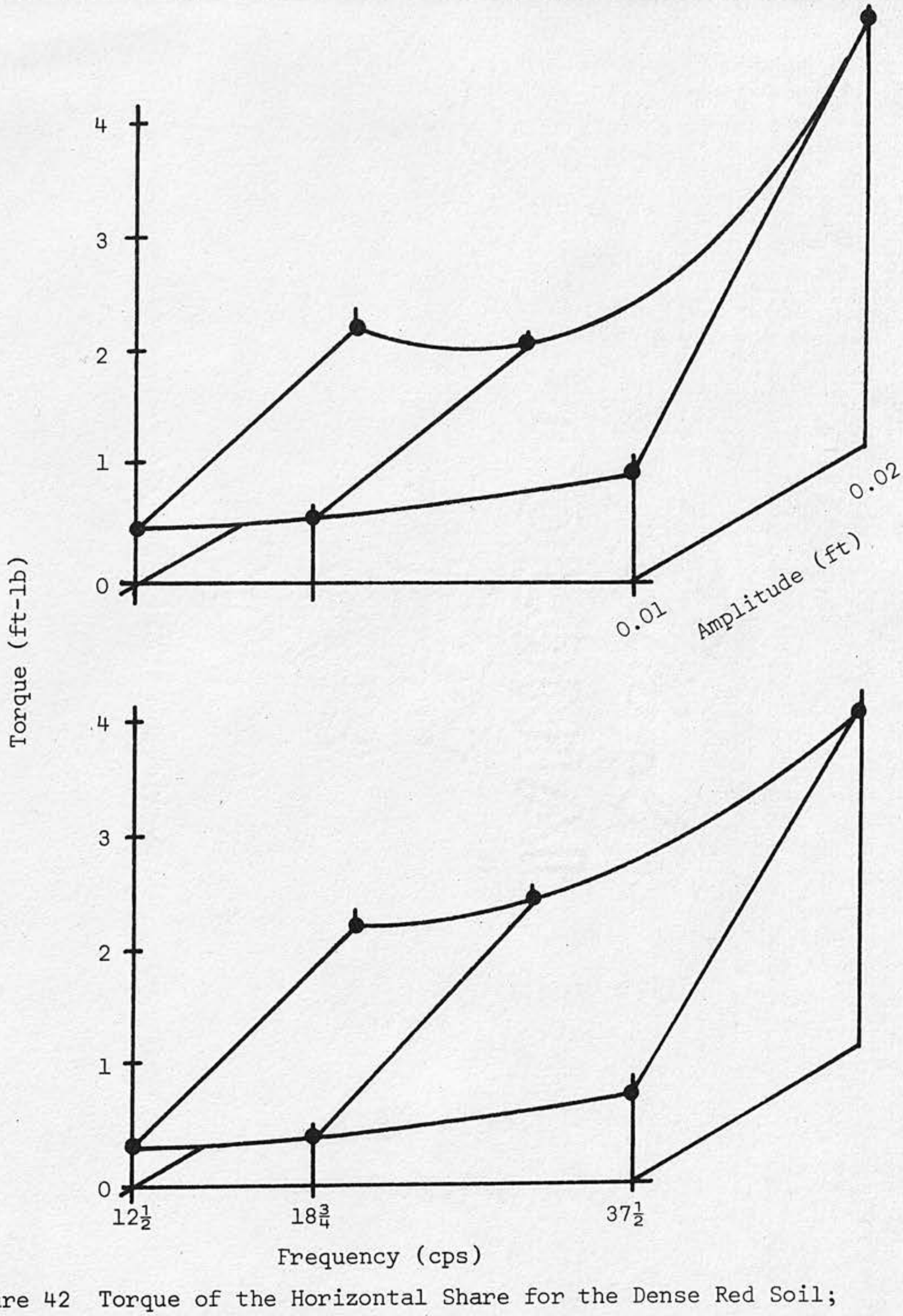


Figure 42 Torque of the Horizontal Share for the Dense Red Soil; top - horizontal plane of oscillation, btm - tilted.

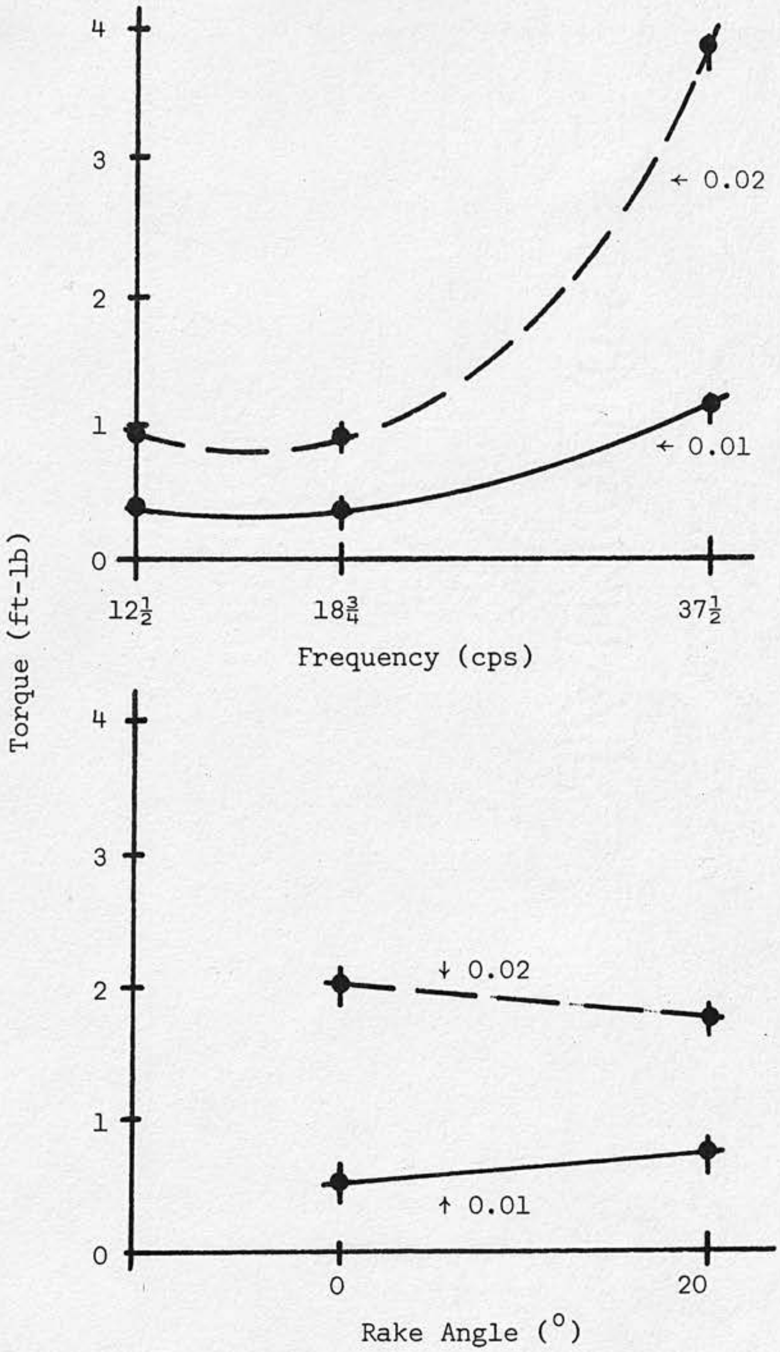


Figure 43 Significant Torque Interactions (first-order) in the Less Dense Red Soil; top and btm - amplitude (ft).

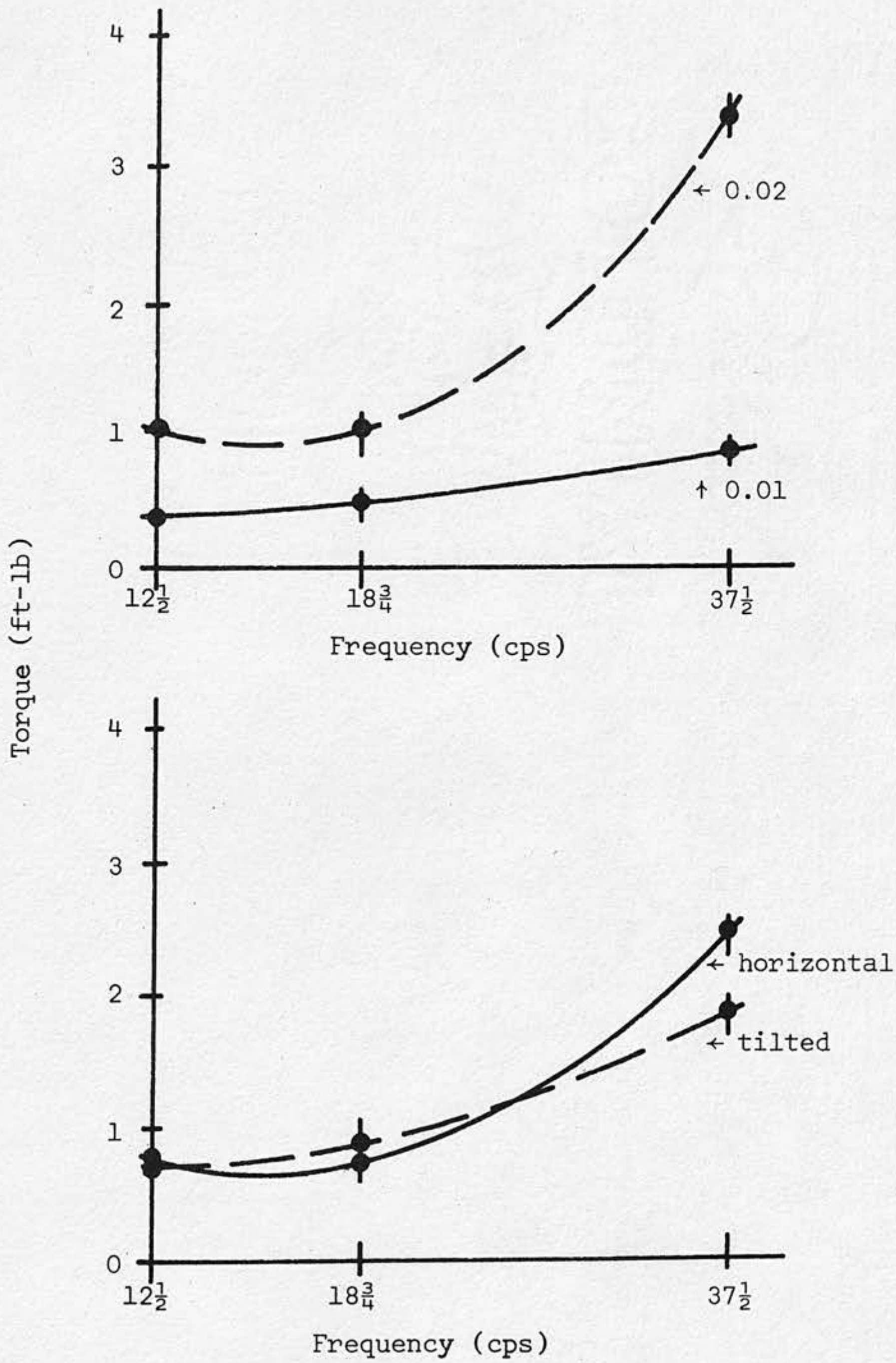


Figure 44 Significant Torque Interactions (first-order) in the Dense Red Soil; top - amplitude (ft), btm - plane of oscillation.

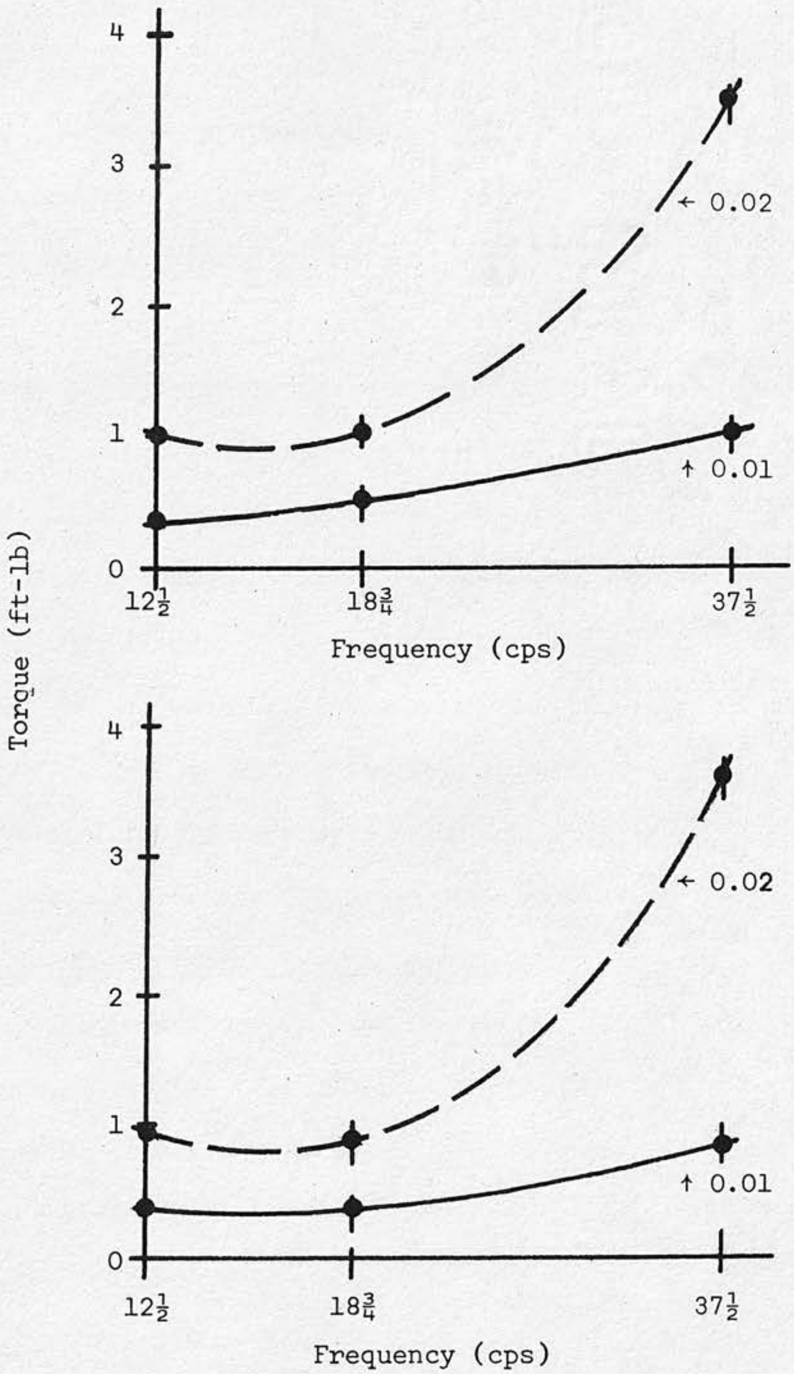


Figure 45 Significant Torque Interactions (first-order) in the Brown Soil; top - less dense, amplitude (ft), btm - dense, amplitude (ft).

plane of oscillation-amplitude interaction, they occurred for only one soil and density. As argued previously (draught response), any conclusion drawn from these interactions would be limited and not on a firm basis. In view of this, discussion of them has not been attempted. Part of the same argument is used for not attempting a discussion of the significant third-order interaction. It occurred only in the dense brown soil.

Total Horsepower of the Horizontal Share

The analysis of variance of the THP for the horizontal share for each soil and density may be seen in Table 24. In this case the blocks were significant only for the less dense brown soil, largely because of the lack of response of the blocks that occurred for the SHP. For the THP, the consistent main effects (significant) were frequency and amplitude. The effect of the latter is very likely due to the SHP response. On the other hand, frequency was a consistent main effect for both the DHP and SHP and, therefore, for the THP as well. The main effects of the rake angle and the plane of oscillation were not consistent, significant only for one soil and density and only at the 5% probability level.

Frequency and Amplitude - Total Horsepower

The THP-frequency and the THP-amplitude relationships may be seen in Figures 46 to 49. The similarity between these response surfaces and that obtained for the torque is an indication that the SHP is the main contributor to the total. As was the case for the torque (and SHP), the THP is directly related to the amplitude and also to the two upper levels of frequency. The differences in the THP are significant as indicated by the analysis of variance (main effects). Comparisons of the response surfaces in Figures 46 and 47 with those in Figures 32 and 34 indicate that the mini-

Table 24: Total Horsepower of the Horizontal Share - Analysis of Variance

Soil - Red/		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	0.51857	0.04714	5.4***	0.36937	0.03358	1.4
Frequency (F)	2	10.72815	5.36408	619.1***	7.34856	3.67428	157.7***
Rake Angle (R)	1	0.04189	0.04189	4.8*	0.01411	0.01411	<1
Plane of Osc. (H)	1	0.00394	0.00394	<1	0.06480	0.06480	2.8
Amplitude (A)	1	3.17488	3.17488	366.4***	3.72008	3.72008	159.6***
FR	2	0.04242	0.02121	2.4	0.02409	0.01205	<1
FH	2	0.00326	0.00163	<1	0.32540	0.16270	7.0***
FA	2	4.15188	2.07594	239.6***	3.16625	1.58312	67.9***
RH	1	0.01600	0.01600	1.8	0.00012	0.00012	<1
RA	1	0.14120	0.14120	16.3***	0.00023	0.00023	<1
HA	1	0.08401	0.08401	9.7***	0.00915	0.00915	<1
FRH	2	0.01143	0.00571	<1	0.01856	0.00928	<1
FRA	2	0.08649	0.04325	5.0*	0.00502	0.00251	<1
FHA	2	0.01309	0.00656	<1	0.18333	0.09167	3.9*
RHA	1	0.02971	0.02971	3.4	0.00700	0.00700	<1
FRHA	2	0.01461	0.00731	<1	0.00395	0.00197	<1
Residual	37	0.31191	0.00866		0.86228	0.02330	
Total	71	19.37346			16.12230		

* P < 5%, *** P < 0.5%

1 - one observation missing

Table 24: Cont'd.

Soil - Brown/		Less Dense[1]			Dense		
Source of Variation	DF	SS	MS	F	SS	MS	F
Blocks (B)	11	0.19376	0.01761	2.1*	0.38989	0.03544	1.9
Frequency (F)	2	10.99230	5.49615	654.0***	10.00945	5.00472	268.1***
Rake Angle (R)	1	0.03297	0.03297	3.9	0.00023	0.00023	<1
Plane of Osc. (H)	1	0.07298	0.07298	8.7*	0.00311	0.00311	<1
Amplitude (A)	1	3.04805	3.04805	362.7***	3.98702	3.98702	214.1***
FR	2	0.07823	0.03911	4.6*	0.03410	0.01705	<1
FH	2	0.00569	0.00284	<1	0.11051	0.05525	3.0
FA	2	3.63839	1.81919	216.5***	4.44619	2.22310	119.4***
RH	1	0.02847	0.02847	3.4	0.03240	0.03240	1.7
FA	1	0.00005	0.00005	<1	0.03068	0.03068	1.6
HA	1	0.05285	0.05285	6.3***	0.03868	0.03868	2.1
FRH	2	0.01419	0.00709	<1	0.06195	0.03097	1.7
FRA	2.	0.00186	0.00093	<1	0.02826	0.01413	<1
FHA	2	0.01577	0.00788	<1	0.01377	0.00688	<1
RHA	1	0.00653	0.00653	<1	0.00107	0.00107	<1
FRHA	2	0.00398	0.00199	<1	0.19930	0.09965	5.4**
Residual	37	0.30255	0.00840		0.68907	0.01862	
Total	71	18.48859			20.07567		

* P < 5%, ** P < 1%, *** P < 0.5%

1 - one observation missing

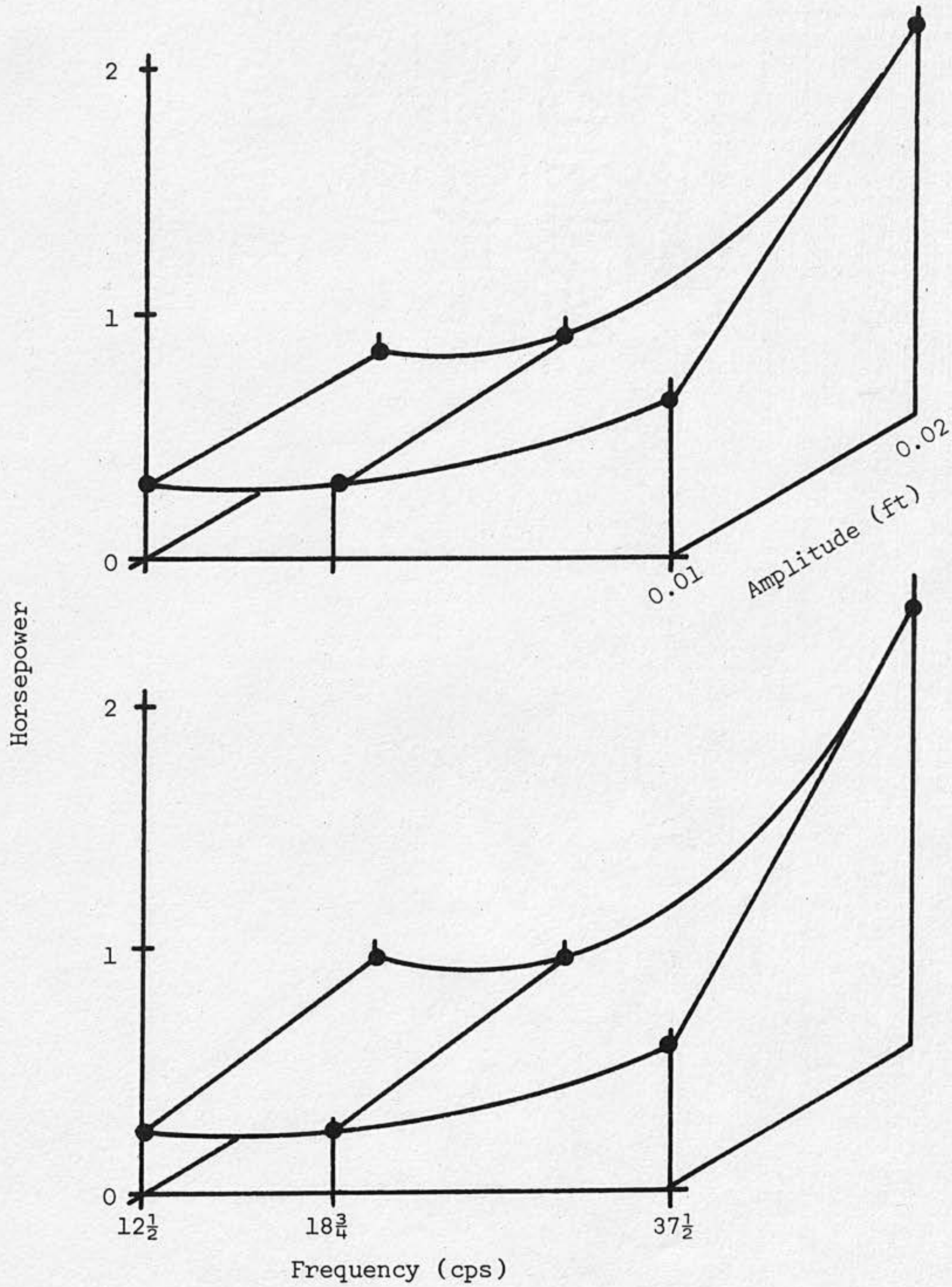


Figure 46 Total Horsepower Requirements of the Horizontal Share for the Less Dense Red Soil; top - horizontal plane of oscillation, btm - tilted.

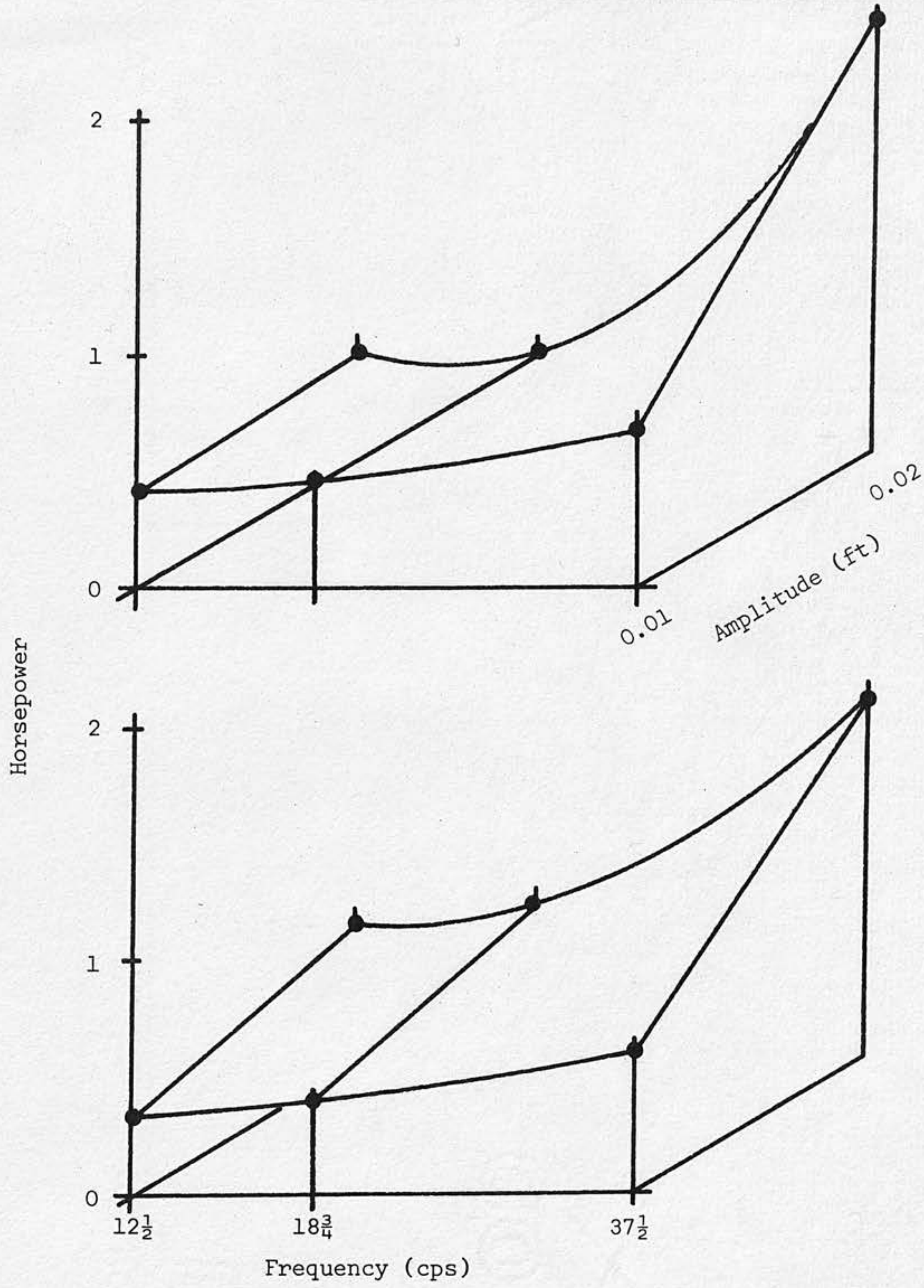


Figure 47 Total Horsepower Requirements of the Horizontal Share for the Dense Red Soil; top - horizontal plane of oscillation, btm - tilted.

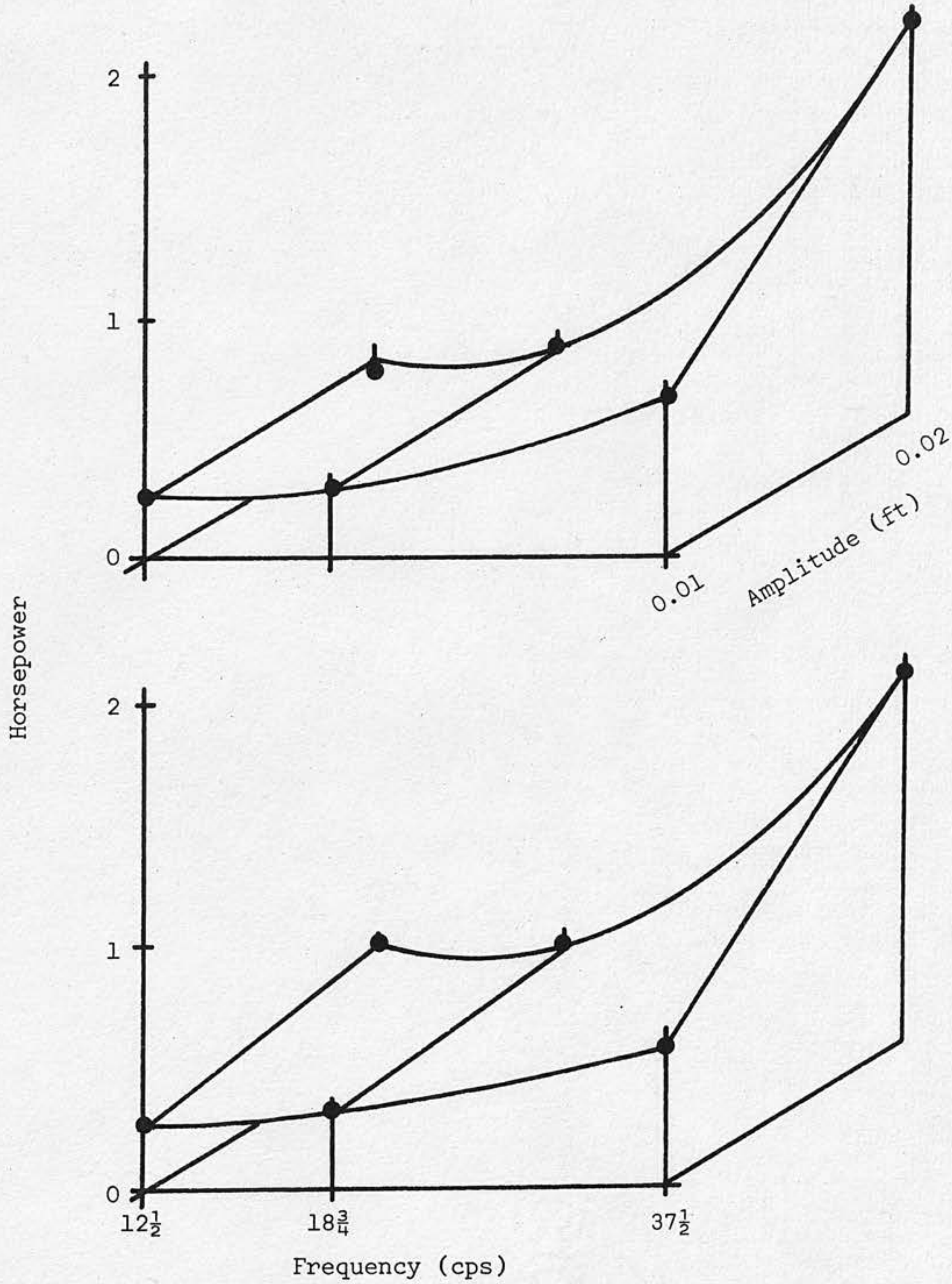


Figure 48 Total Horsepower Requirements of the Horizontal Share for the Less Dense Brown Soil; top - horizontal plane of oscillation, btm - tilted.

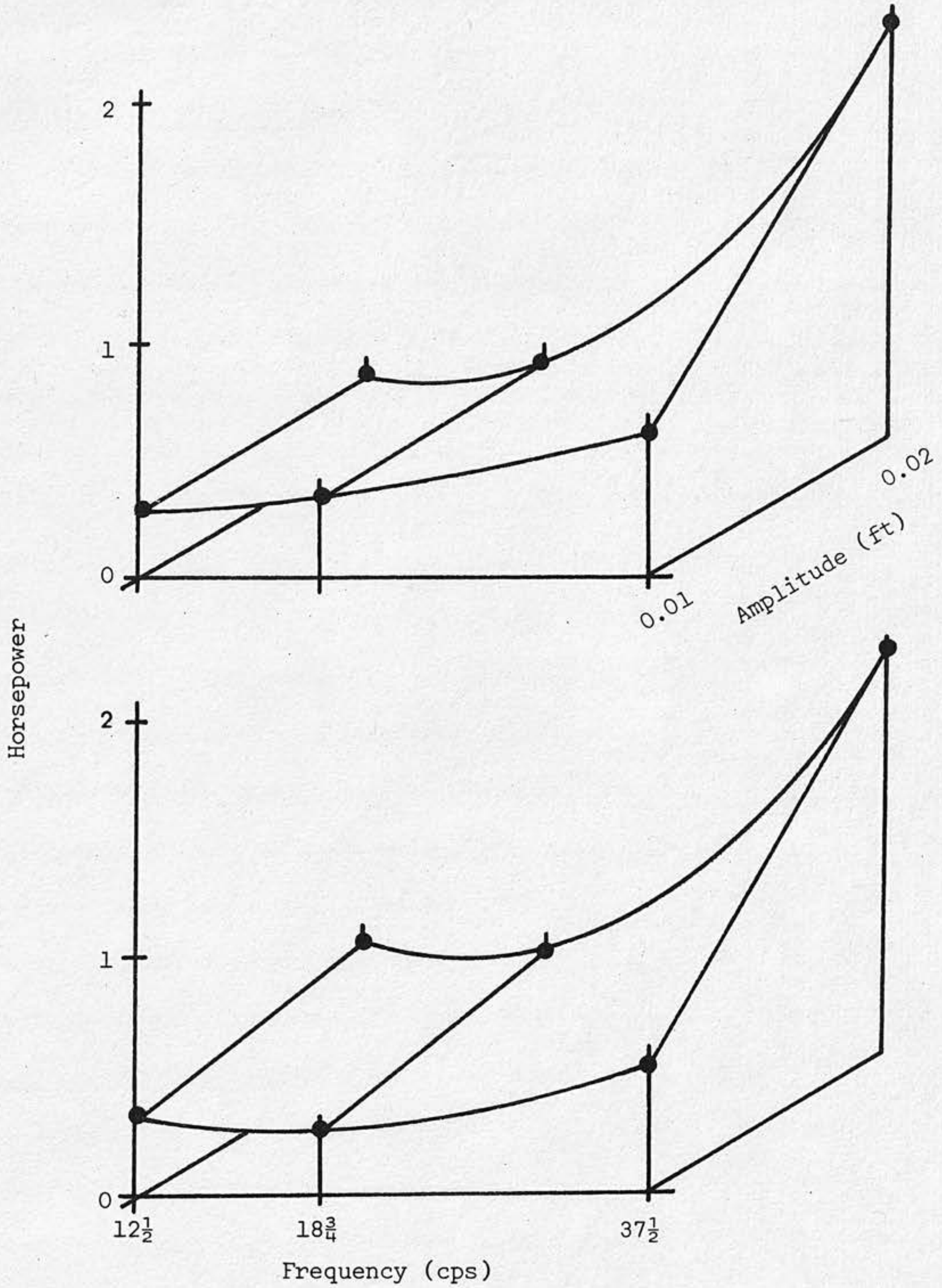


Figure 49 Total Horsepower Requiremints of the Horizontal Share for the Dense Brown Soil; top - horizontal plane of oscillation, btm - tilted.

mum draught does not coincide with the minimum THP or energy. Though this observation confirms the suggestion of Senator (75), it does not necessarily follow that reversal of the tool in the soil is wasted energy.

Interactions - Total Horsepower

With the exception of the rake angle-frequency interaction for the less dense brown soil, the significant first-order interactions may be seen in Figures 50 to 53. In general these interactions are the same as those obtained for the torque. Again the frequency-amplitude interaction is the most consistent, occurring for both soils and densities. The plane of oscillation-amplitude interaction (Figure 53), which is significant at the 5% probability level for the torque in the less dense soils, is significant at the 0.5% level for the THP. There was a decrease in the THP when the plane of oscillation was tilted for the minimum amplitude, but an increase for the maximum amplitude. The changes in the THP were small in comparison with the responses obtained for the factors of frequency and amplitude. The same applies to the plane of oscillation-frequency interaction (Figure 51-btm) for the dense red soil and the rake angle-frequency interaction (not illustrated) for the less dense brown soil. The two significant second-order and the one third-order interactions are the same as for the torque and, for the same reasons advanced, no discussion of them has been attempted.

Comparison of Horsepower Means

The means of the DHP, SHP and THP for each soil and density are given in Table 25 and their comparisons (t-test) in Table 26. The differences in the DHP are significant except between the less dense red and brown soils. On the other hand, none of the differences in the SHP are significant. It is evident that the SHP, within the range of the experiment, is

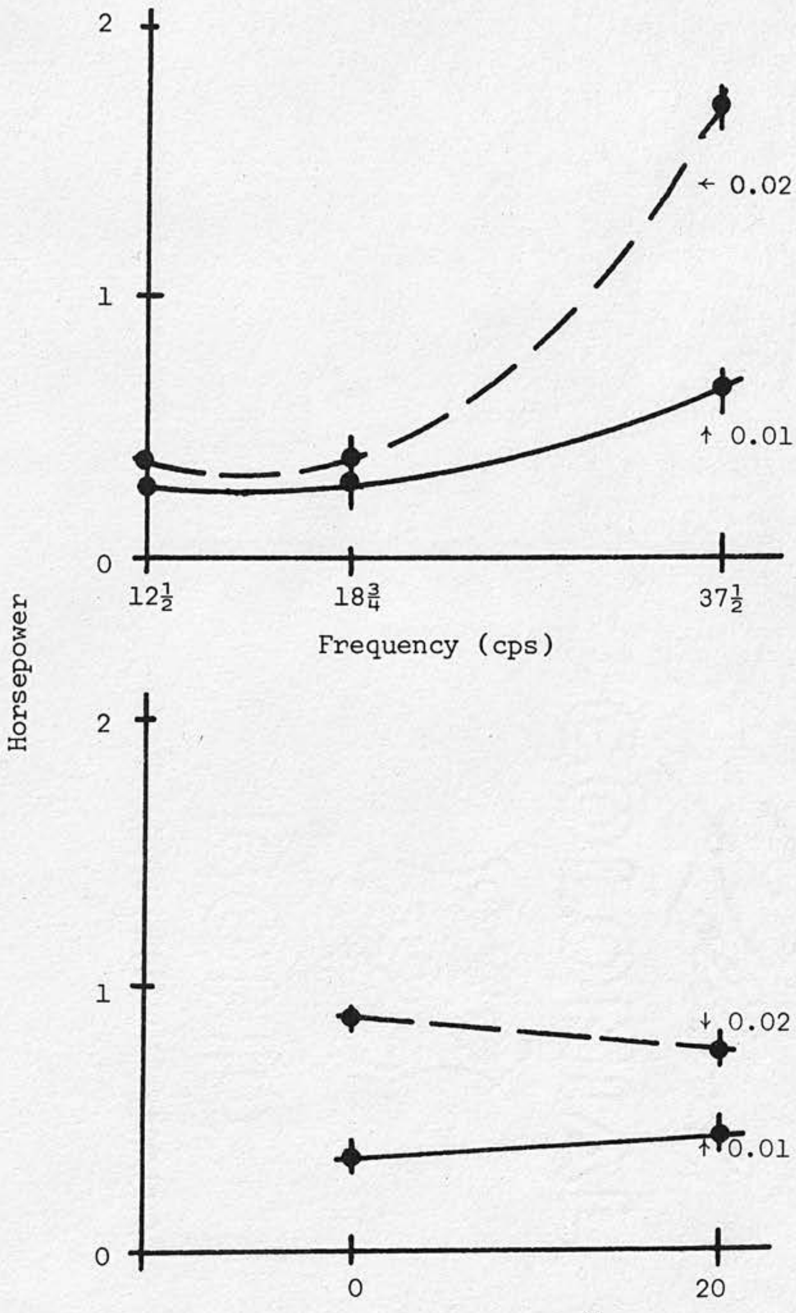


Figure 50 Significant Total Horsepower Interactions (first-order) in the Less Dense Red Soil; top and btm - amplitude (ft).

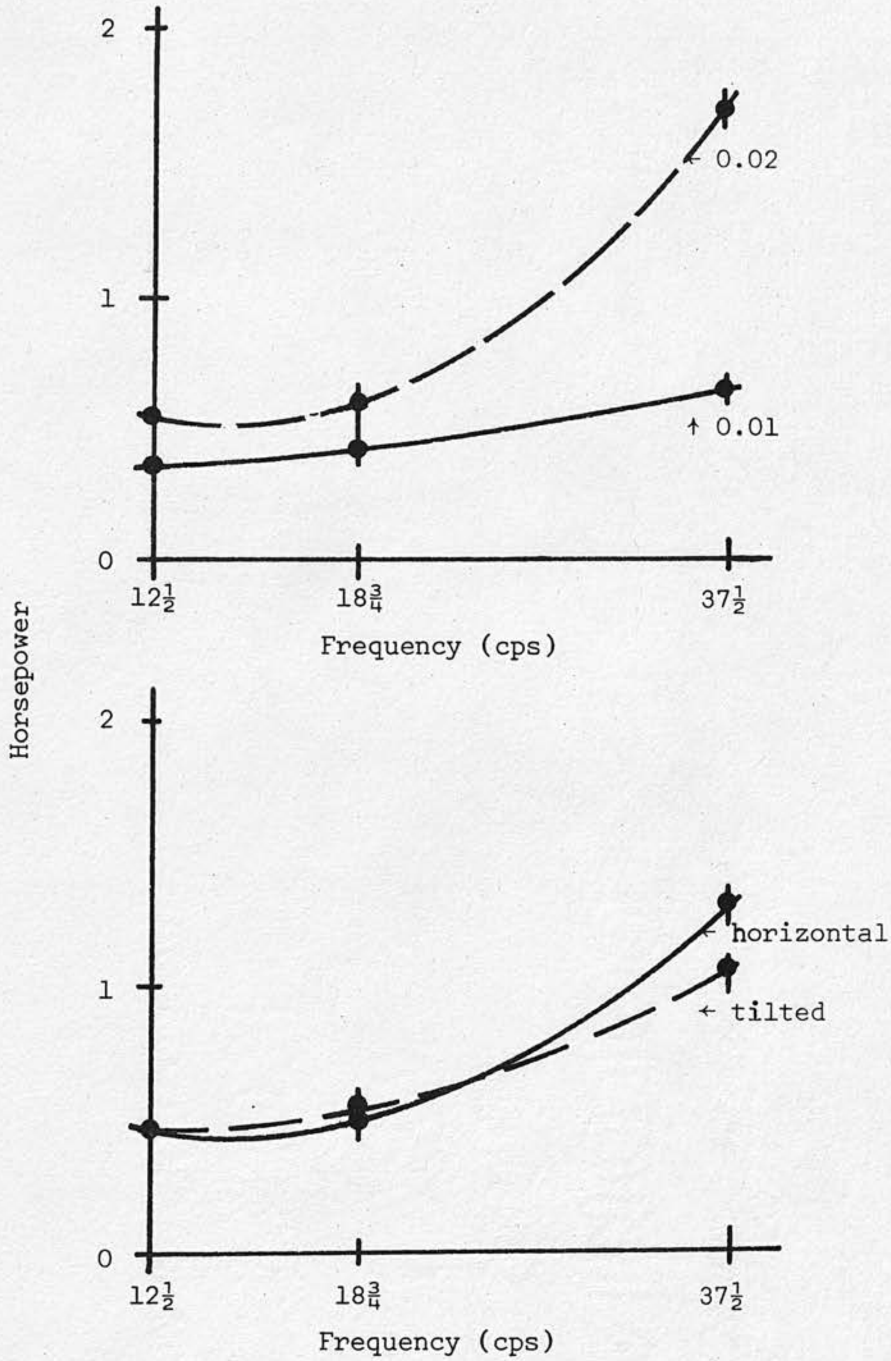


Figure 51 Significant Total Horsepower Interactions (first-order) in the Dense Red Soil; top - amplitude (ft), btm - plane of oscillation.

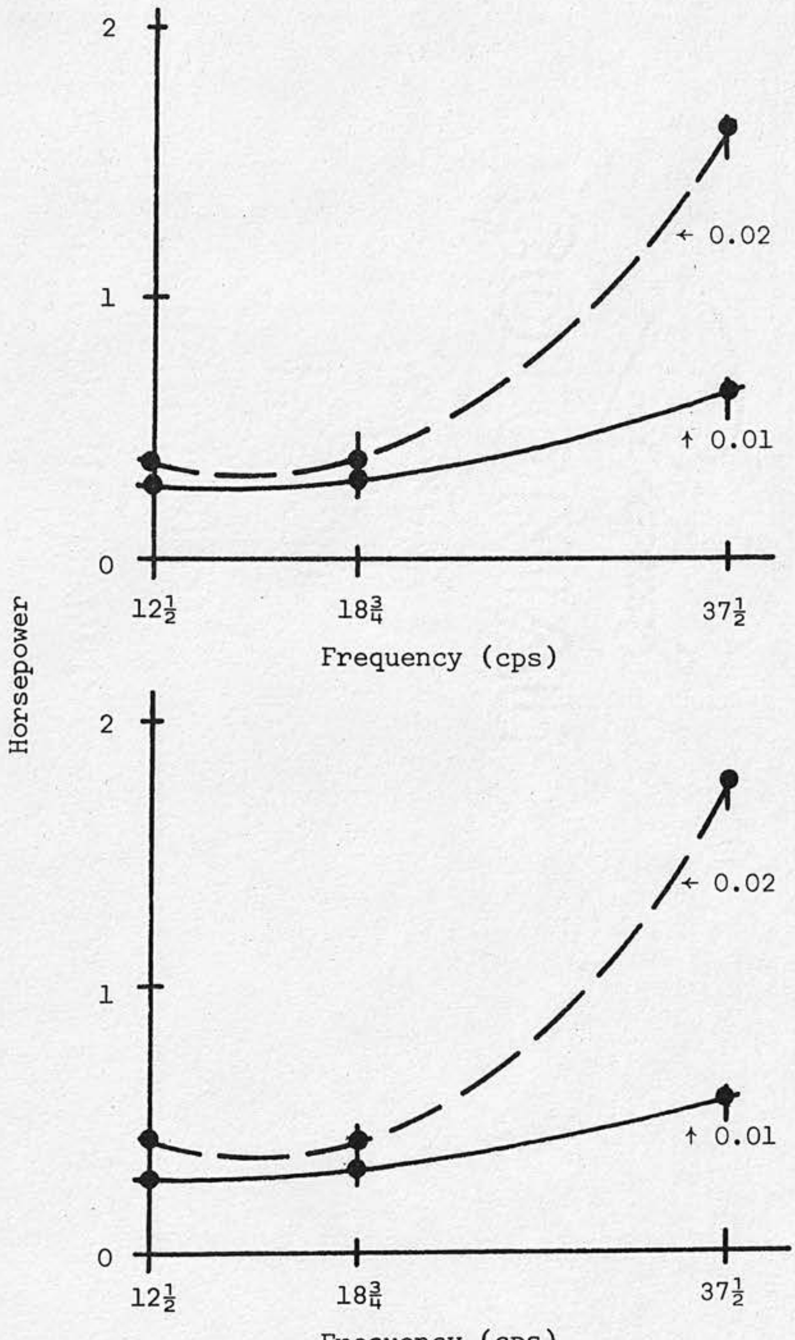


Figure 52 Significant Total Horsepower Interactions (first-order) in the Brown Soil; top - less dense, amplitude (ft), btm - dense, amplitude (ft).

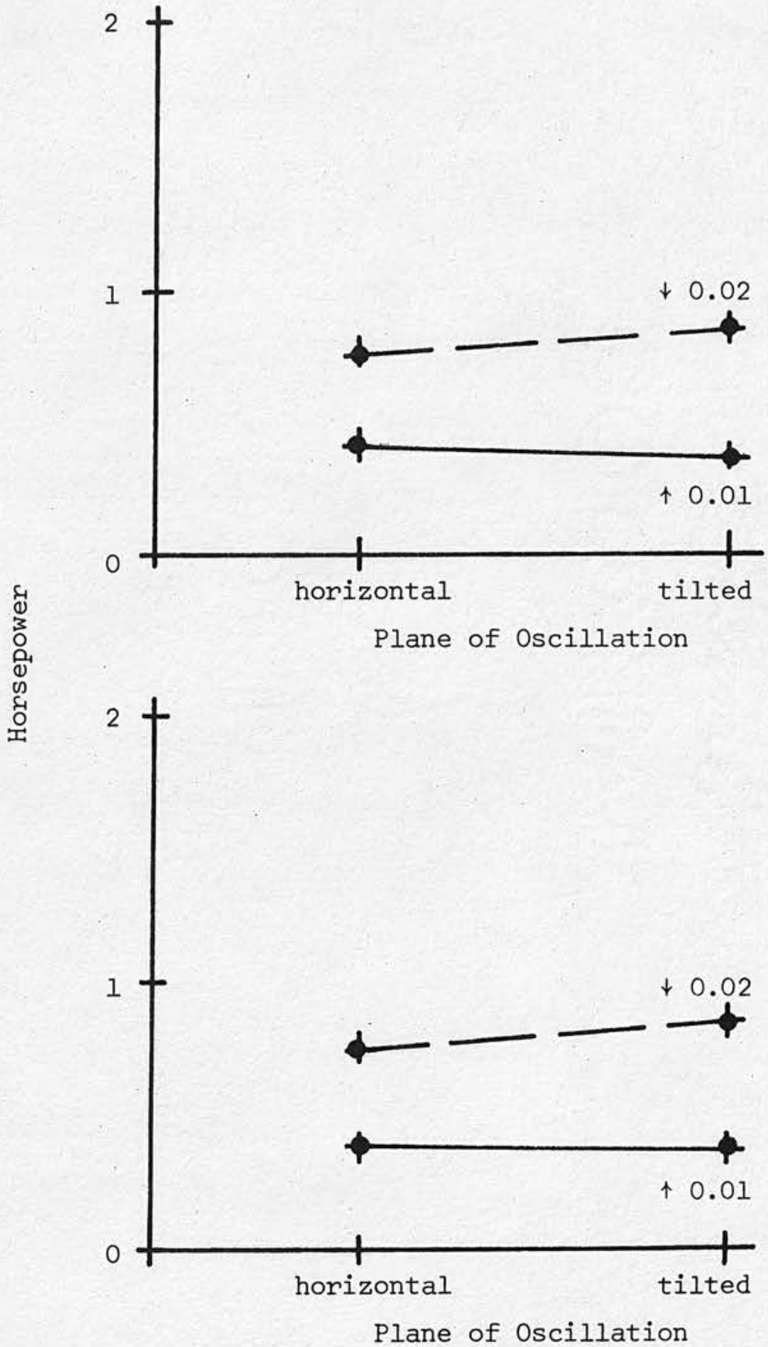


Figure 53 Significant Total Horsepower Interactions (first-order) in the Less Dense Soils; top - red, amplitude (ft), btm - brown, amplitude (ft).

Table 25 Means of the Draught, Torque and Power Requirements

Soil	Red		Brown	
Density	Less Dense	Dense	Less Dense	Dense
Draught (lb)	58	100	56	71
Drawbar Horsepower	0.16	0.28	0.16	0.20
Torque (ft-lb)	1.2	1.2	1.3	1.2
Shaft Horsepower	0.44	0.42	0.44	0.42
Total Horsepower	0.60	0.70	0.59	0.62

Table 26 Comparison of the Horsepower Means (t-test)

<u>Drawbar Horsepower</u>

```
Less Dense Red  →  0.96   ←  Less Dense Brown
        →  5.26***       9.89***  ←
   ↓                                  ↓
  9.41***           ×            6.14***
   ↑                                  ↑
        →  9.89***       5.26***  ←
     Dense Red  →  6.27*** ←  Dense Brown
```

<u>Shaft Horsepower</u>

```
Less Dense Red  →  0.00   ←  Less Dense Brown
        →  0.64          0.80  ←
   ↓                                  ↓
  0.72              ×            0.70
   ↑                                  ↑
        →  0.80          0.64  ←
     Dense Red  →  0.00   ←  Dense Brown
```

<u>Total Horsepower</u>

```
Less Dense Red  →  0.21   ←  Less Dense Brown
        →  0.70          3.57**  ←
   ↓                                  ↓
  3.40**            ×            0.86
   ↑                                  ↑
        →  3.57**        0.70    ←
     Dense Red  →  2.41   ←  Dense Brown
```

independent of the soil type and density. As for the THP, three of the six comparisons are significant at the 1% probability level.

The observation that the SHP (and torque) is independent of the soil type and density has two implications. In the first place, it may account for some of the difference between Eggenmüller and Dubrovoskii. As noted in Chapter 5, Eggenmüller (26) reports the total power requirements of a vibratory body to be 30% to 100% greater than for a rigid one, whereas Dubrovoskii (24) reports a 35% reduction. Some of the difference may be due to differences in the density of the soil that they experimented with.

The other implication is in the application of a vibratory tool. For economy, a plough or cultivator would be used as a rigid tool-implement for tilling a soft, low density soil. In a hard, high density soil, on the other hand, the implement would be used as a vibratory tool-implement to reduce the draught and avoid the necessity of adding ballast to the tractor. Ballast is usually required to develop sufficient traction in this situation, but it will increase the mechanical impedance of the traffic sole.

Dimensional Analysis

The draught (d) of the horizontal share has been defined (see Chapter 8) as a function of the following independent variables;

$$\alpha,\ \theta,\ f,\ A,\ \gamma,\ \dot{x},\ L.$$

In the experimental work, the travel rate ($\dot{x}$) and the dimensions of the share (L) were held constant and would normally be eliminated. The travel rate is retained, however, so that the dimensionless ratio, λ ($\lambda = \dot{x}/2fA$), will appear in the analysis. By retaining the share dimension, the draught numeric or dimensionless ratio ($d/\gamma L^3$) can be the same as used by Luth and Wismer (59). If the dimension L is the share width, then the ratio is a force per unit width.

According to Luth and Wismer (59), the number of dimensionless ratios required in the analysis must be equal to the number of variables (independent and dependent), less the number of fundamental units which, in this case, are three (force, length and time). The number of dimensionless ratios required, therefore, is five. The following relationship, using $d/\gamma L^3$ and λ, will satisfy this requirement.

$$d/\gamma L^3 = f(\alpha, \theta, \lambda, A/L). \qquad - 1$$

The requirement for the dimensionless ratio, A/L, can be readily seen in Figures 54 and 55. The plotted points (means) appear to be grouped, depending on whether the amplitude was the minimum or the maximum. In other words, the dimensionless ratio for the draught is not only a function of λ, but of the amplitude as well.

According to the analysis of variance, the effect of the rake angle and the plane of oscillation with respect to the draught was limited. In view of this, they may be eliminated from equation 1 without altering it appreciably; that is,

$$d/\gamma L^3 = f(\lambda, A/L). \qquad - 2$$

The relationship suggested by Figures 54 and 55 is exponential which may be satisfied, along with equation 2, by the following;

$$d/\gamma L^3 = m\lambda^n \text{ where} \qquad - 3$$

$$m,n = f(A/L). \qquad - 4$$

As only two amplitudes were used in the experimental work, the relationship of m,n and A/L must be assumed to be linear; that is, equation 4 is satisfied by;

$$m = a_1 + b_1 A/L.$$

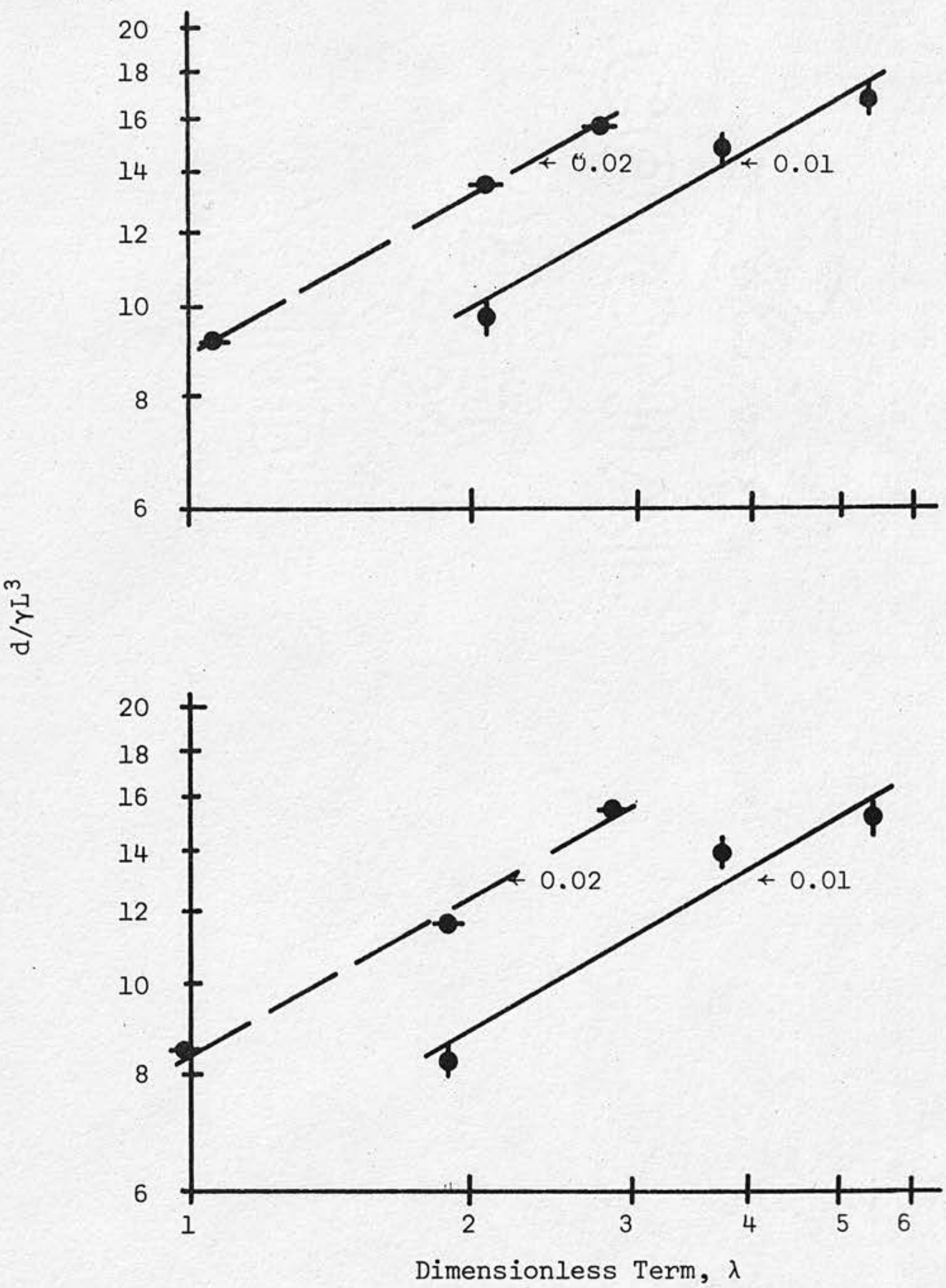


Figure 54 The Relationship between the Dimensionless Draught Term and λ for the Less Dense Soils; top - red, amplitude (ft), btm - brown, amplitude (ft).

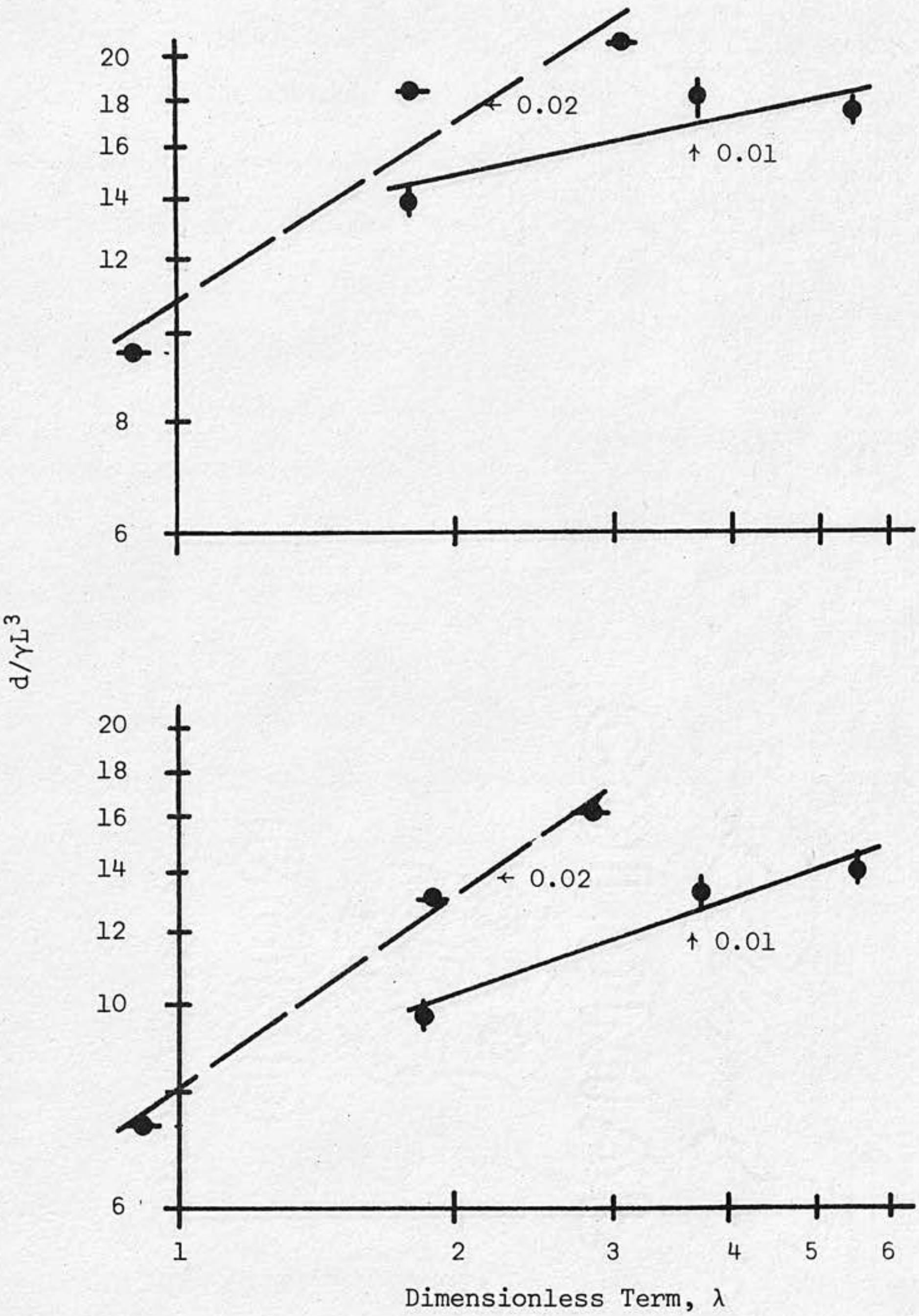


Figure 55 The Relationship between the Dimensionless Draught Term and λ for the Dense Soils; top - red, amplitude (ft), btm - brown, amplitude (ft).

$$n = a_2 + b_2\ A/L.$$

The final form of the analysis is;

$$d/\gamma L^3 = (a_1 + b_1\ A/L)\ \lambda^{a_2 + b_2\ A/L}. \qquad - 5$$

Using a method suggested by Steel and Torrie (87), the coefficients, m and n, were determined for both soils and densities. Subsequently, the regression coefficients a_1, a_2, b_1 and b_2 were calculated. The following relationships were obtained when the regression coefficients were substituted into equation 5. For a horizontal share and

for the less dense red soil,

$$d/\gamma L^3 = (3.9 + 103\ A/L)\ \lambda^{0.65 - 2.1\ A/L}$$

for the dense red soil,

$$d/\gamma L^3 = (16 - 145\ A/L)\ \lambda^{-0.32 + 22.7\ A/L}$$

for the less dense brown soil,

$$d/\gamma L^3 = (4.2 + 88\ A/L)\ \lambda^{0.52 + 0.58\ A/L}$$

for the dense brown soil,

$$d/\gamma L^3 = (9.3 - 46\ A/L)\ \lambda^{0.20 + 21.6\ A/L}$$ where

d is the draught in lb,

γ is the bulk density in lb/ft^3,

L is the width of the share in ft,

A is the amplitude in ft,

and for λ,

$\mathring{x}$ is the travel rate in ft/s,

f is the frequency in cps.

For these equations the following qualifications are required;

- the travel rate is 1.5 ft/s,
- the frequency is between $12\frac{1}{2}$ and $37\frac{1}{2}$ cps,

- the amplitude is between 0.01 and 0.02 ft,
- the rake angle is between 3 and 20^{o},
- the vertical displacement of the tool does not exceed 0.006 ft,
- the soil is between a sandy loam and loam (remoulded),
- the soil density is between 65 and 85 lb/ft^3.

It is apparent from the regression coefficients, a_1, a_2, b_1, b_2, and Figures 54 and 55, that the equations for the two soils could be combined without much loss of accuracy, but not for the two densities. This suggests that the bulk density variable, γ, is not an adequate parameter in this instance. Some additional variable of the soil is required. It does not appear to be the soil viscosity because one would expect the viscosity to reflect the soil type and not the density. In view of this, and because of the heterogeneity of the residual, no relationship for the two soils, or for the two densities, or for the soils and densities together, was attempted.

A similar dimensional analysis for the torque is not feasible because the torque and SHP, according to the analysis of variance, are independent of the bulk density. Because there is no other variable which contains a force unit, it is impossible to include the torque in a dimensionless ratio. In order to summarize the torque results, the methods of multiple regression are used.

<u>Multiple Regression</u>

Using the statistical analysis "package" in APL at the University of Alberta, regression coefficients were obtained for the torque data. Because the reduction in the sum of squares by the two factors of rake angle and plane of oscillation were so small, they were eliminated[1]. The indica-

1 This was expected from the results of the analysis of variance.

indicated relationships for a 5 in. horizontal share are;

for the less dense red soil,

$$t = -2.2 + 0.072\ f + 124\ A$$

for the dense red soil,

$$t = -2.4 + 0.069\ f + 130\ A$$

for the less dense brown soil,

$$t = -2.4 + 0.076\ f + 125\ A$$

for the dense brown soil,

$$t = -2.0 + 0.058\ f + 132\ A \quad \text{where}$$

f is the frequency in cps and A is the amplitude in ft. The qualifications specified for the dimensional analysis (draught) apply to the above as well. The similarity in the coefficients is another example of the independence of the torque with respect to the soil type and density.

Soil Tilth

It was argued in Chapter 5 that investigation of vibratory tillage and the resulting soil tilth was of questionable value at this time. On the other hand, to ignore the soil tilth would be to overlook some important consequences of vibratory tillage. As a compromise, photographs of the tilled soil strip (Part 2) were taken for each level of each factor. These photographs may be seen in Plates 10 to 25. They were taken from a position that was almost directly overhead of the soil strip. In some of the photographs (no rake angle) the vertical furrow wall is readily seen and occasionally the groove left by the disk coulter marking the other side of the strip. The length of the soil strip in the plates is approximately one foot.

One of the most obvious differences in the soil tilth is the effect of the rake angle. This has been noted previously (Rake Angle Interactions -

Draught) and was the experience of Johnson and Buchele (50). With the 20° rake angle, the clods almost filled the furrow. Another difference that is readily apparent is the size of the clods. The clod size of the less dense soils is much smaller than it is of the dense soils (compare Plates 12 and 13 with 16 and 17). It was obvious from handling the soil that clods of the red soil were much more durable than were the clods of the brown soil.

There was little change in the soil tilth with respect to the plane of oscillation (compare Plates 10 and 11, 12 and 13, 14 and 15, etc.) or with respect to dimensionless ratio, λ. In some cases, however, such as Plates 11, 12 and 13, there are a greater number of pea-sized clods with λ of 1 and 2' than there were with λ of 4 and 6. This limited response to λ was also the experience of Johnson and Buchele (50), but, on the other hand, there is some evidence of Eggenmüller's (27) superior "crumbling action".

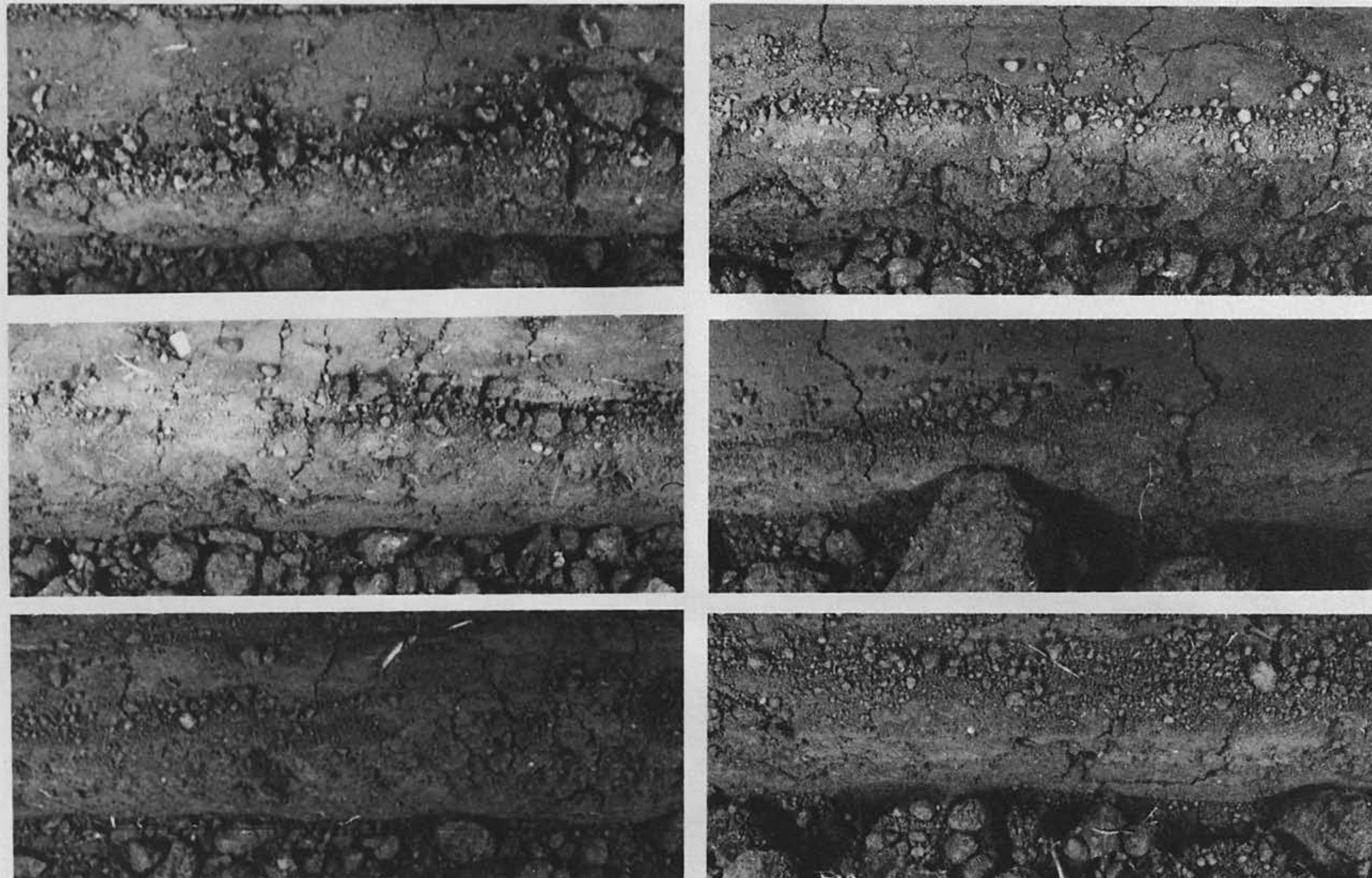


PLATE 10 PULVERIZATION OF THE LESS DENSE RED SOIL; HORIZONTAL PLANE OF OSCILLATION, NO RAKE ANGLE,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,
TOP - $\lambda = 6$, MID - $\lambda = 4$, BTM - $\lambda = 2'$, TOP - $\lambda = 3$, MID - $\lambda = 2$, BTM - $\lambda = 1$

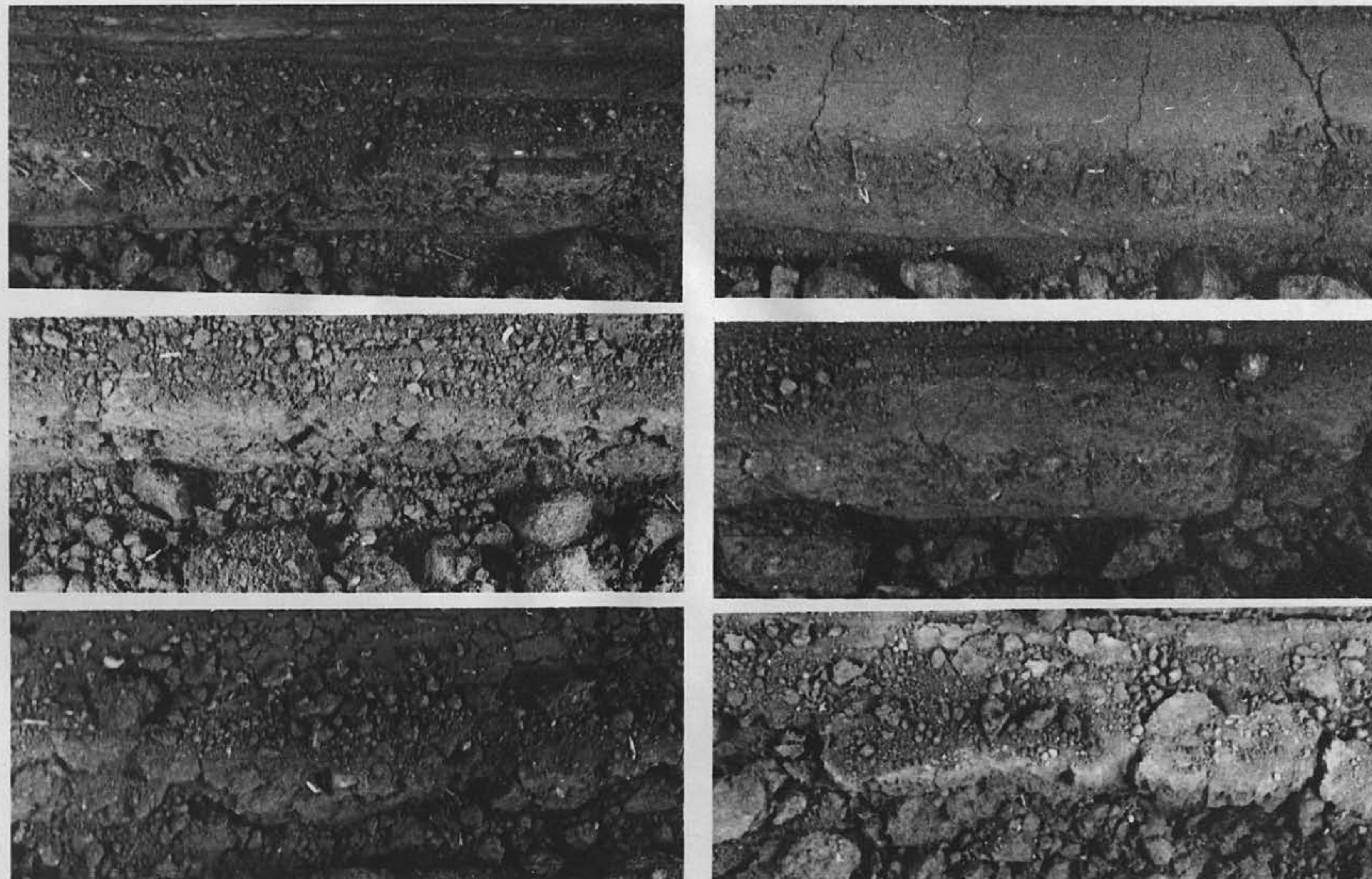


PLATE 11 PULVERIZATION OF THE LESS DENSE RED SOIL; TILTED PLANE OF OSCILLATION, NO RAKE ANGLE,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,
TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

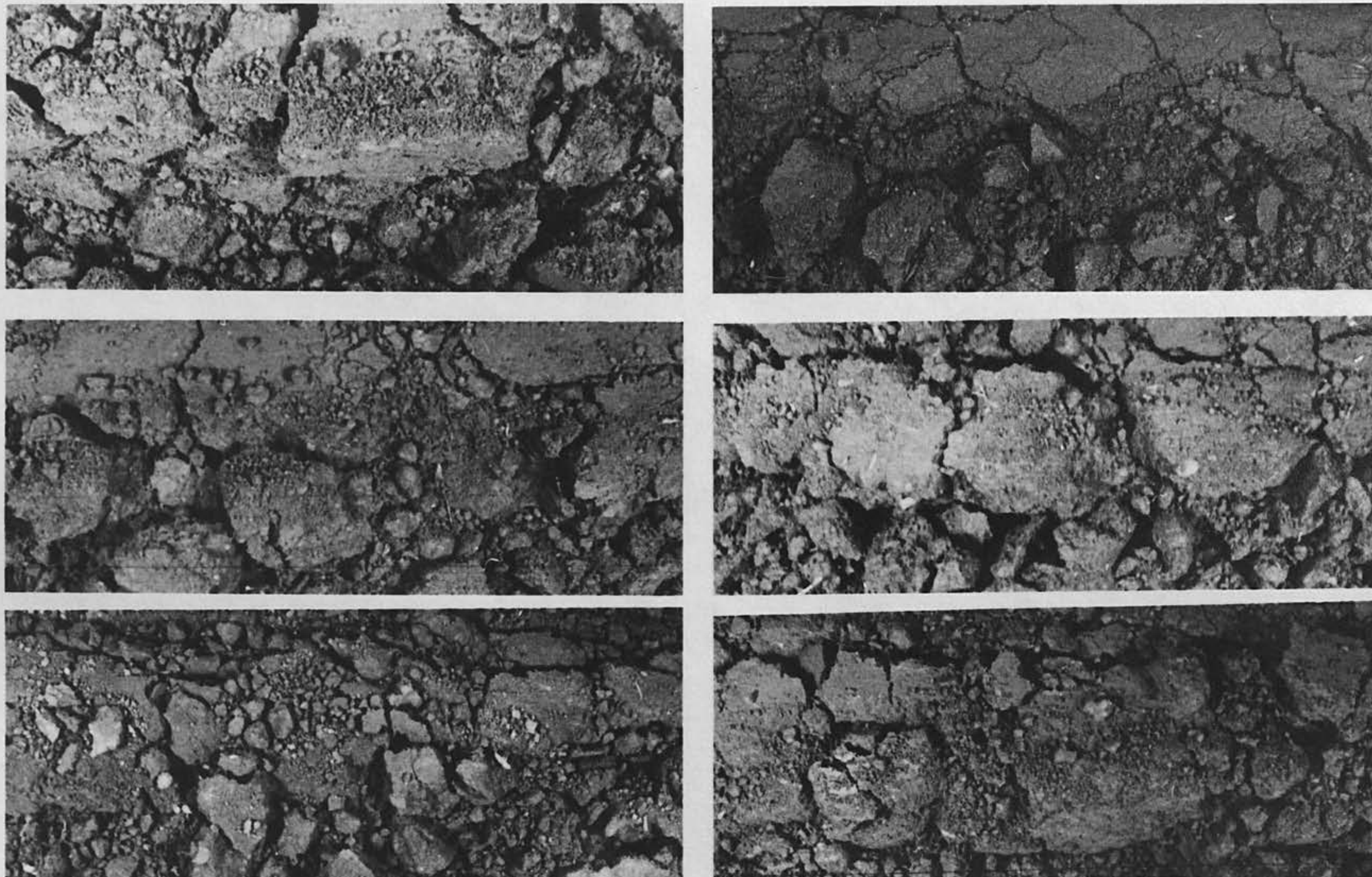


PLATE 12 PULVERIZATION OF THE LESS DENSE RED SOIL; HORIZONTAL PLANE OF OSCILLATION. RALE ANGLE IS 20°,

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT. RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT.

TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

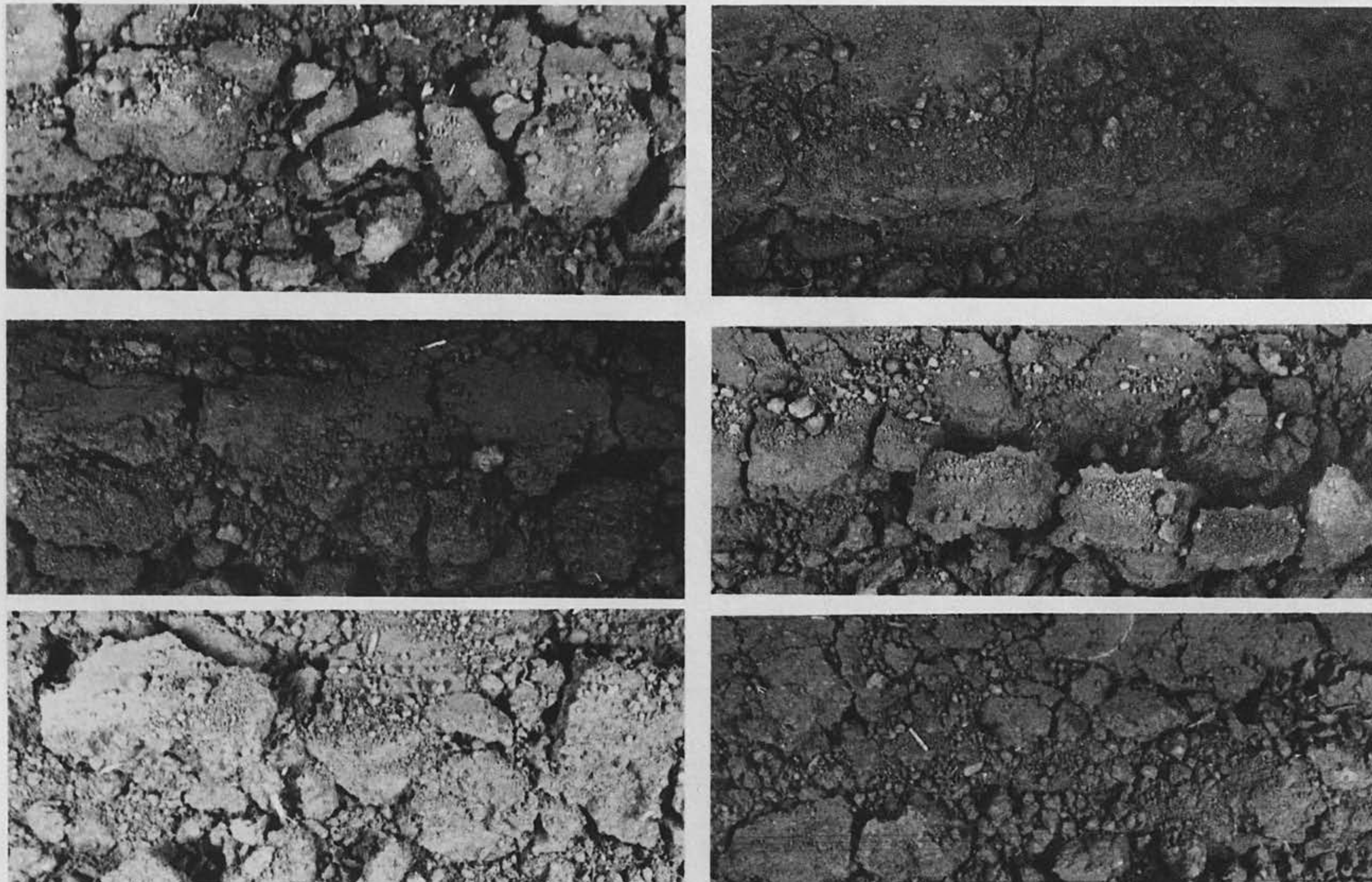


PLATE 13 PULVERIZATION OF THE LESS DENSE RED SOIL; TILTED PLANE OF OSCILLATION, RAKE ANGLE IS 20°.

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,

TOP - $\lambda = 6$, MID - $\lambda = 4$, BTM - $\lambda = 2'$, TOP - $\lambda = 3$, MID - $\lambda = 2$, BTM - $\lambda = 1$

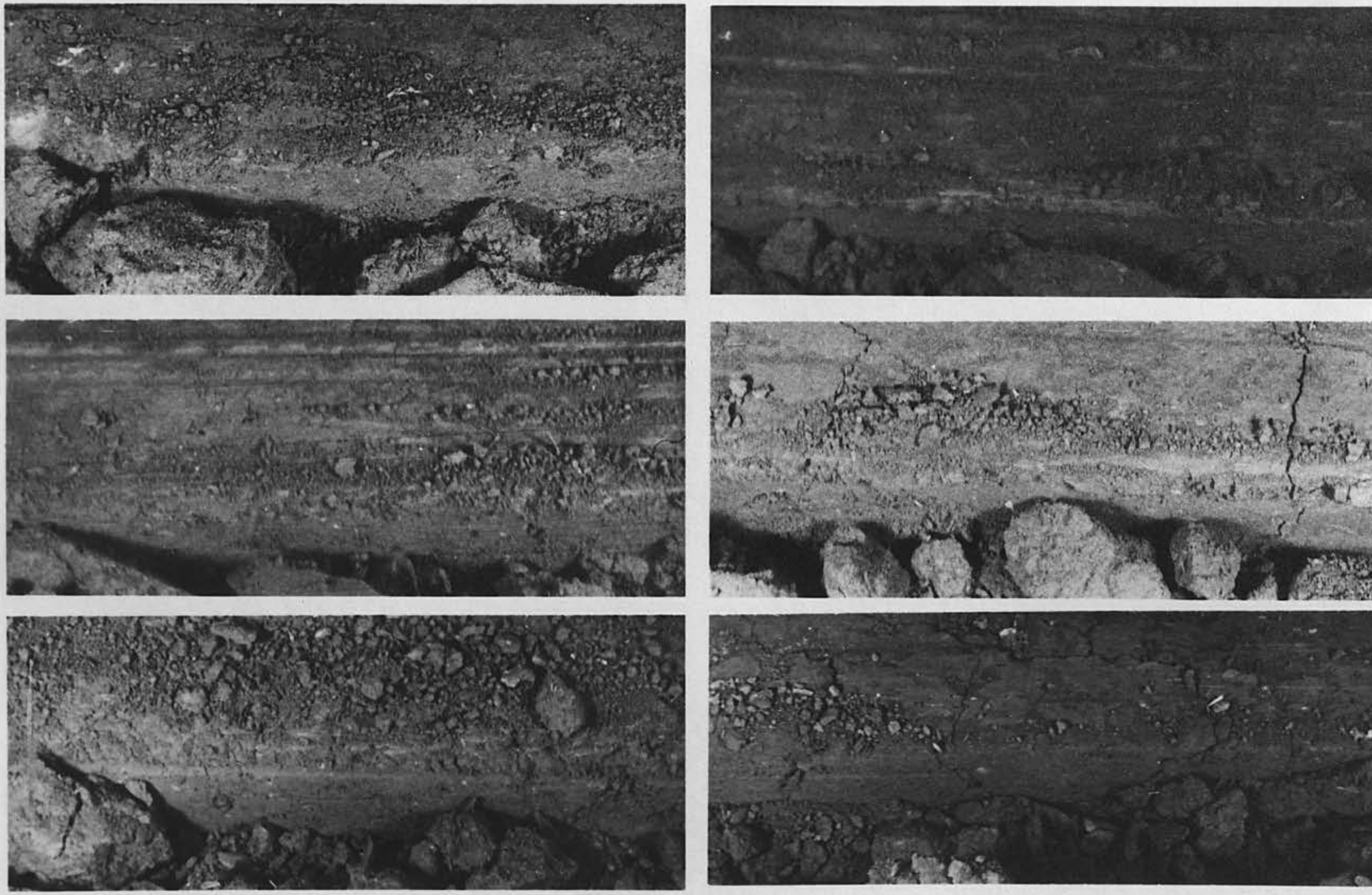


PLATE 14 PULVERIZATION OF THE DENSE RED SOIL; HORIZONTAL PLANE OF OSCILLATION, NO RAKE ANGLE,

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, TOP - λ = 6, MID - λ = 4, BTM - λ = 2',

RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT, TOP - λ = 3, MID - λ = 2, BTM - λ = 1

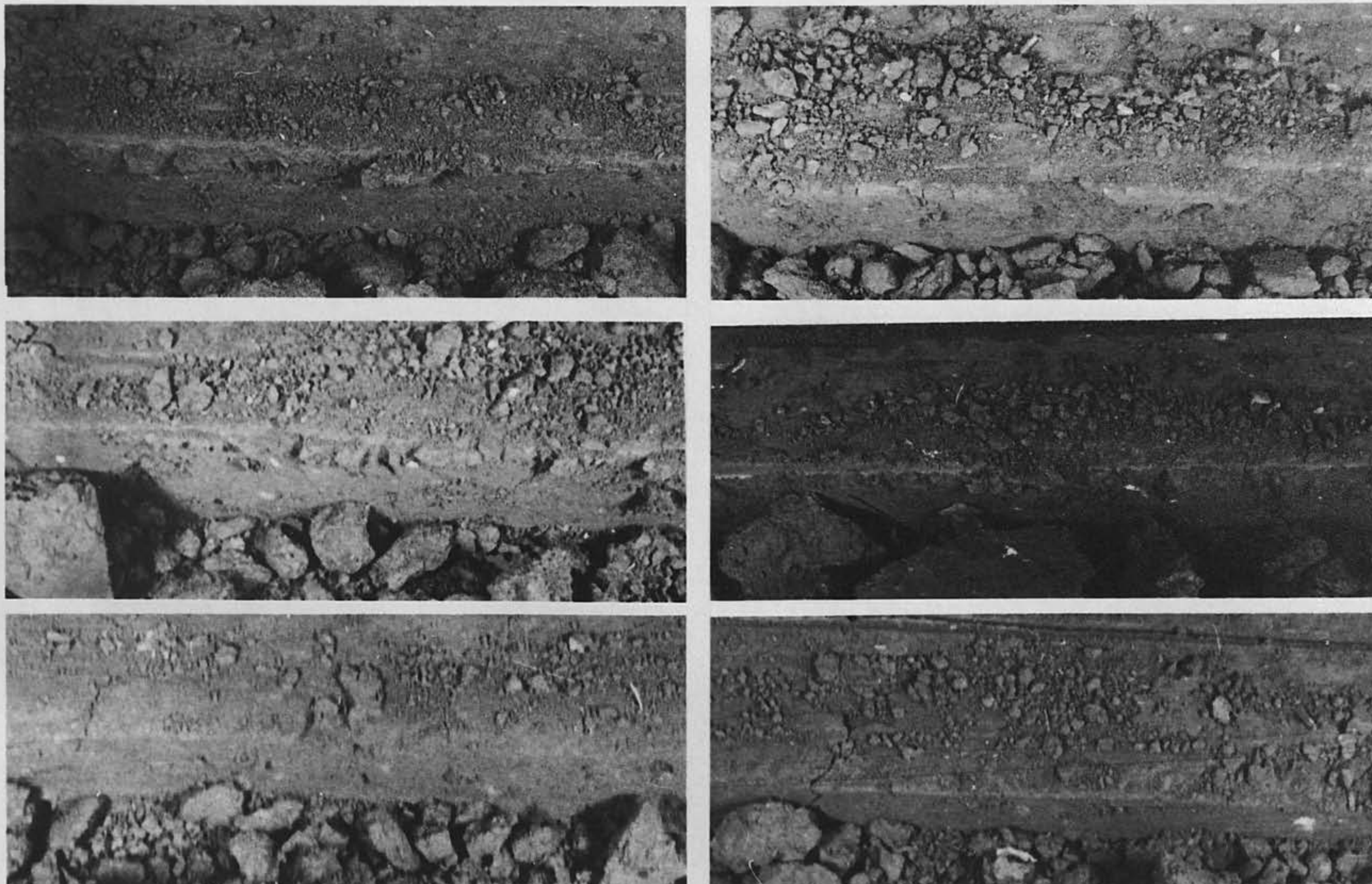


PLATE 15 PULVERIZATION OF THE DENSE RED SOIL; TILTED PLANE OF OSCILLATION, NO RAKE ANGLE.

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT. RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT.

TOP - $\lambda = 6$, MID - $\lambda = 4$, BTM - $\lambda = 2'$, TOP - $\lambda = 3$, MID - $\lambda = 2$, BTM - $\lambda = 1$

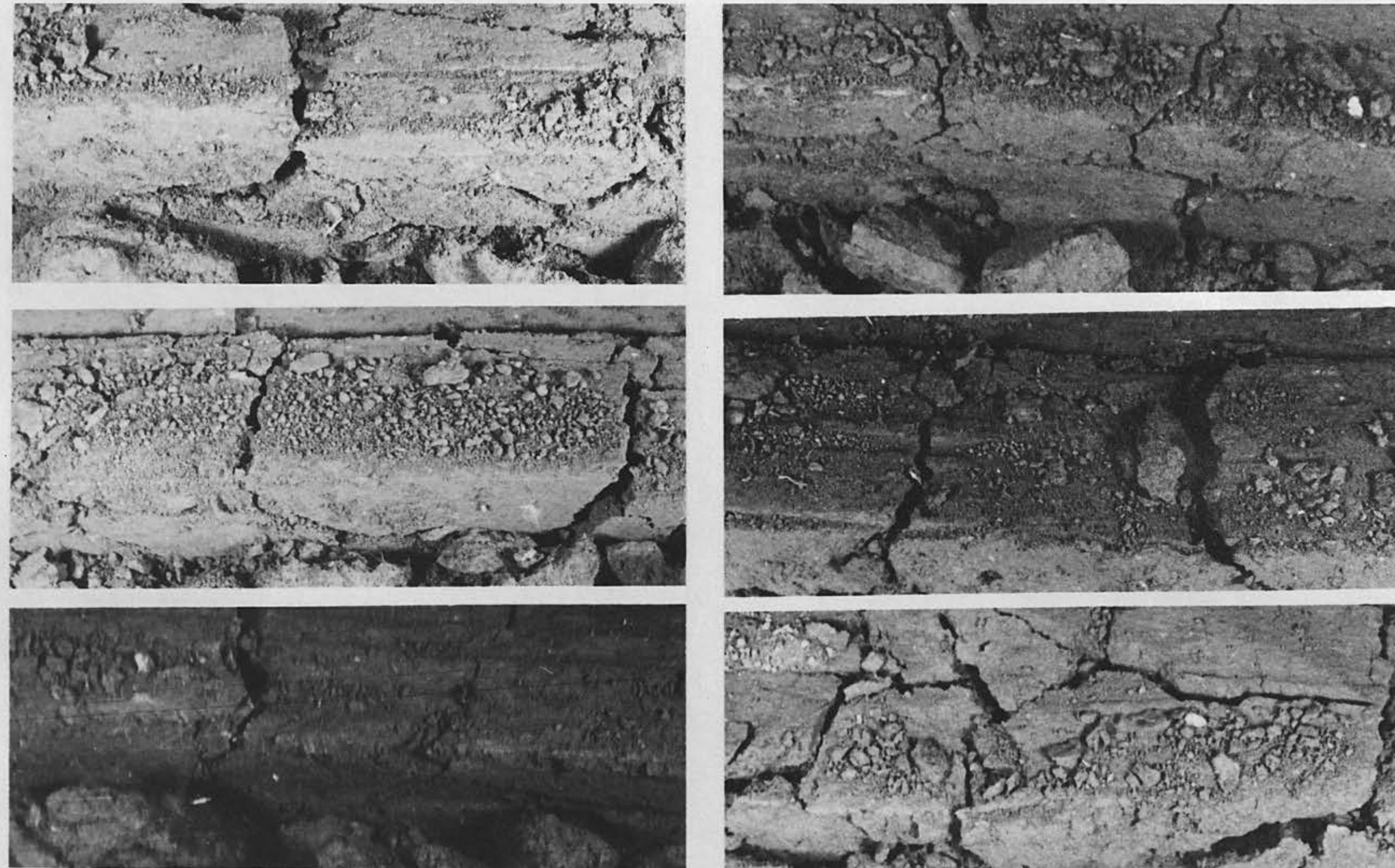


PLATE 16 PULVERIZATION OF THE DENSE RED SOIL; HORIZONTAL PLANE OF OSCILLATION, RAKE ANGLE IS 20°.
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,
TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

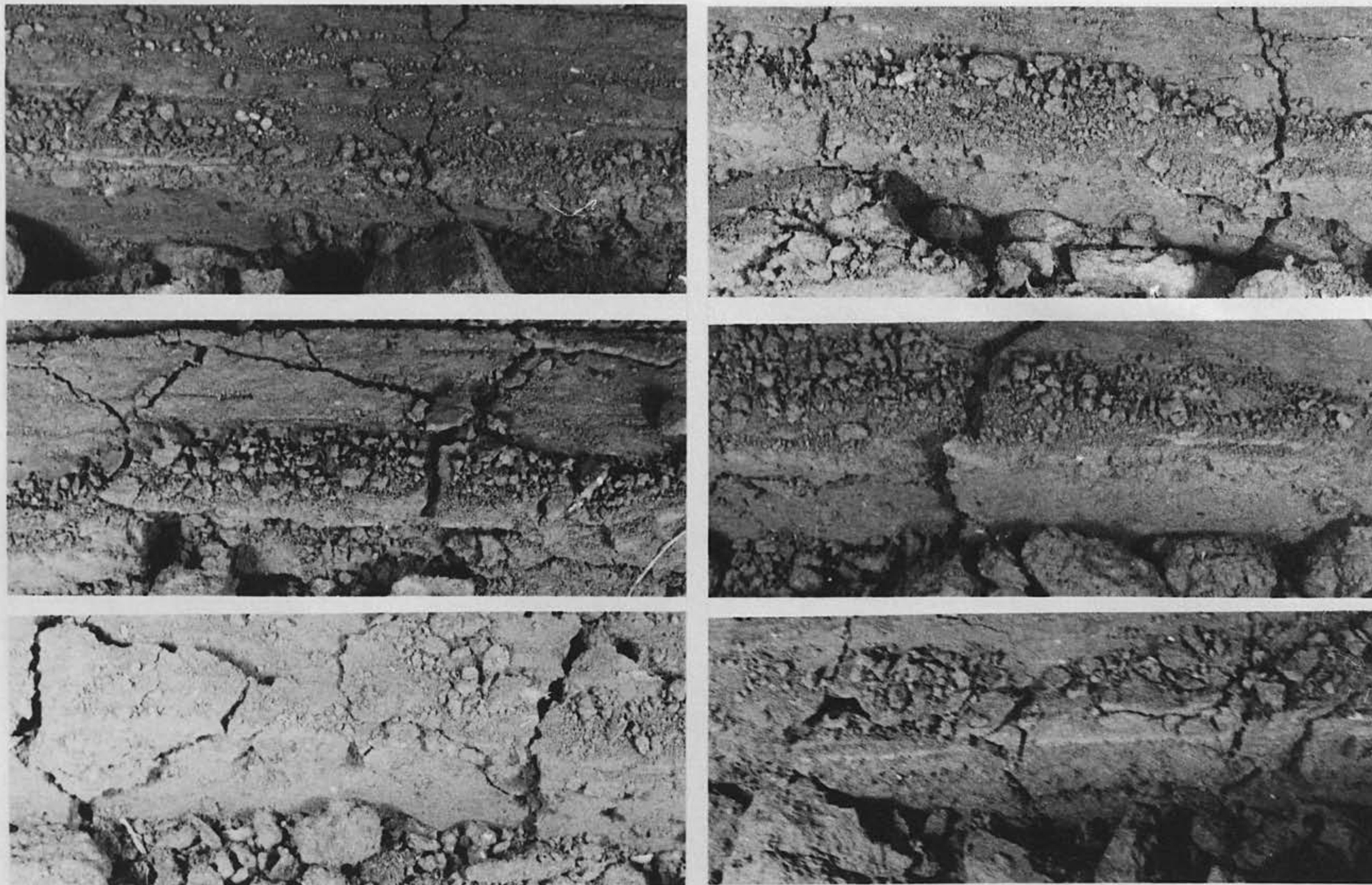


PLATE 17 PULVERIZATION OF THE DENSE RED SOIL; TILTED PLANE OF OSCILLATION, RAKE ANGLE IS 20°,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,
TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

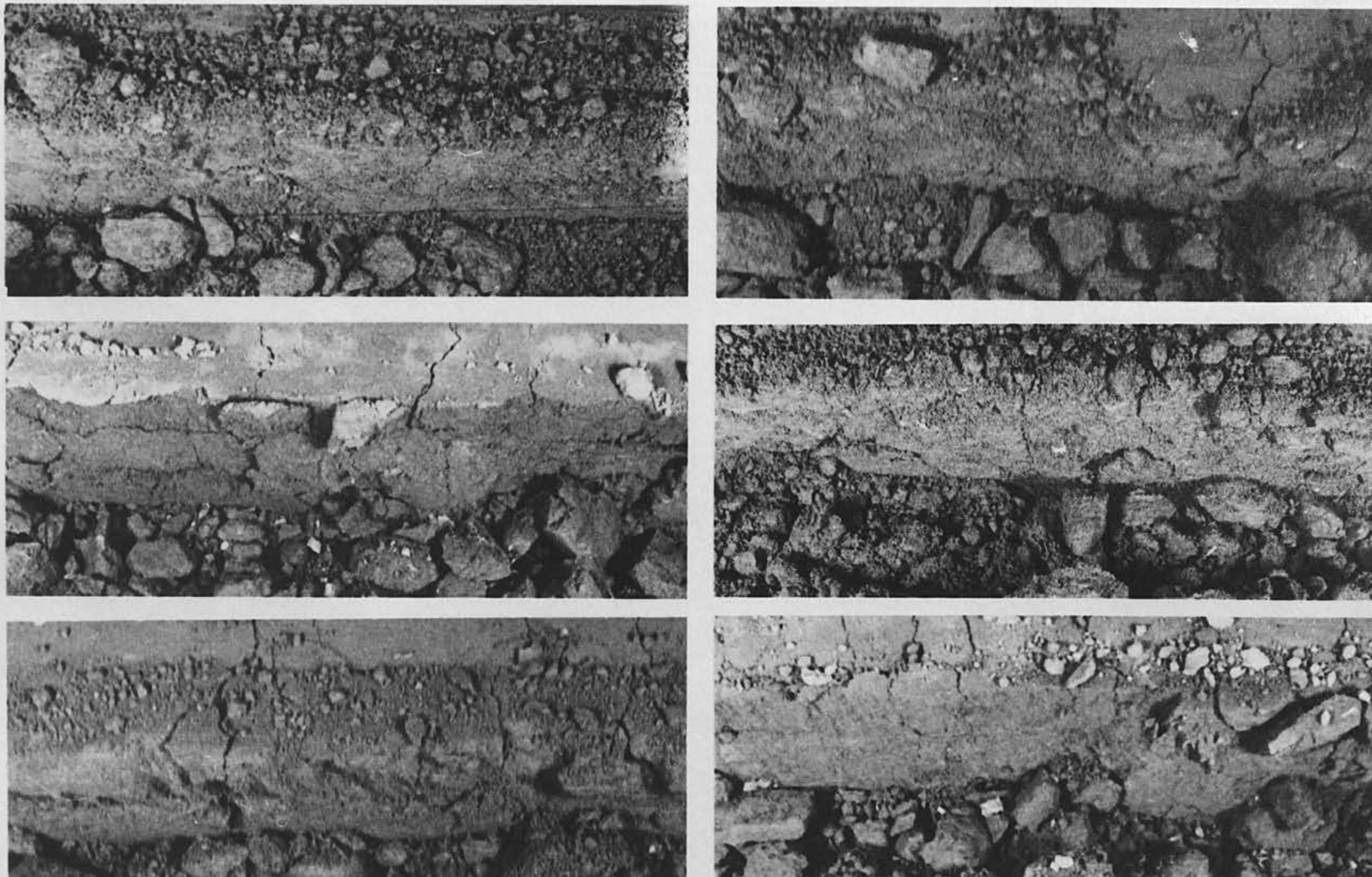


PLATE 18 PULVERIZATION OF THE LESS DENSE BROWN SOIL; HORIZONTAL PLANE OF OSCILLATION, NO RAKE ANGLE,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, TOP - λ = 6, MID - λ = 4, BTM - λ = 2',
RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT, TOP - λ = 3, MID - λ = 2, BTM - λ = 1

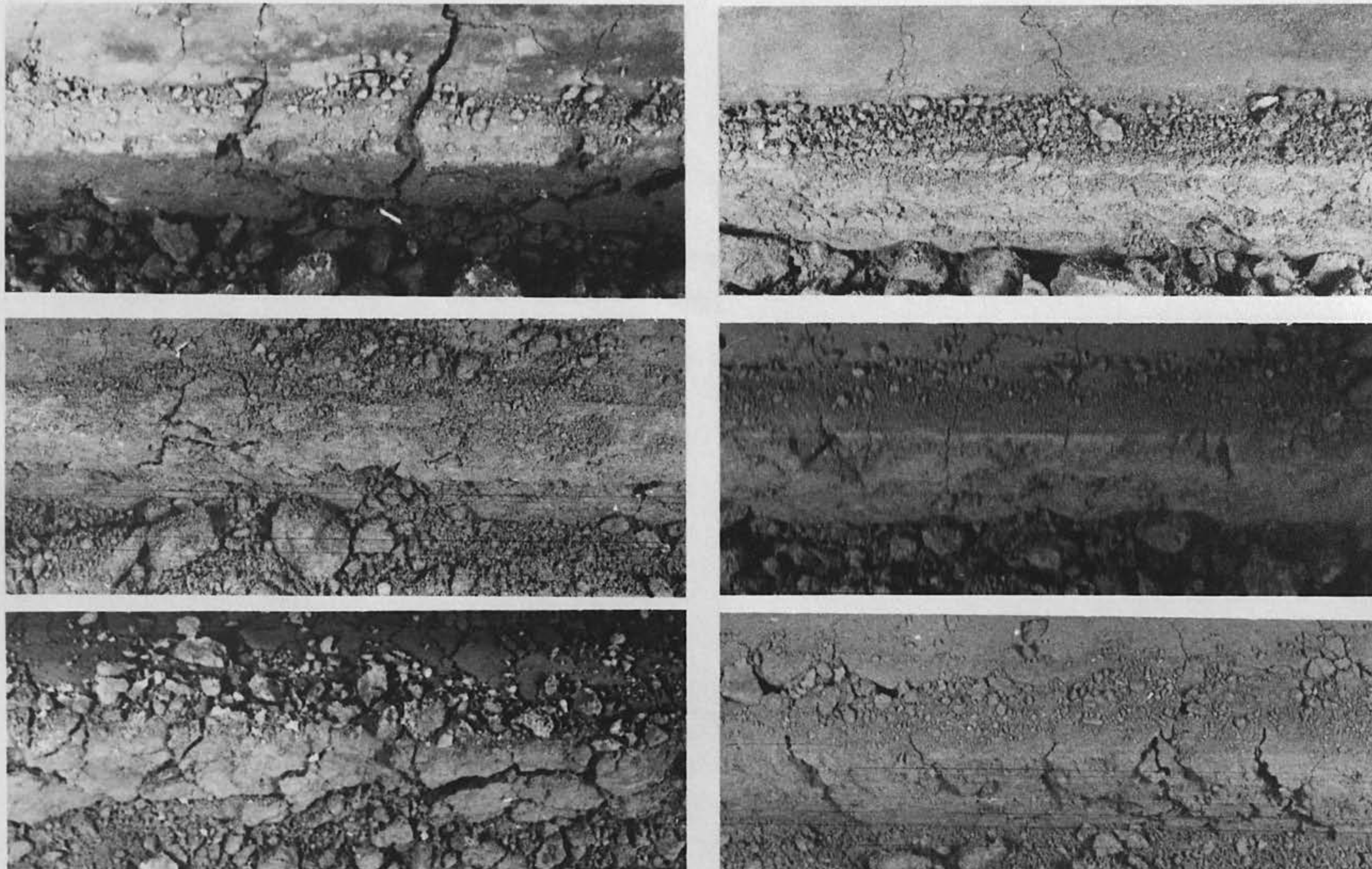


PLATE 19 PULVERIZATION OF THE LESS DENSE BROWN SOIL; TILTED PLANE OF OSCILLATION, NO RAKE ANGLE,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,
TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

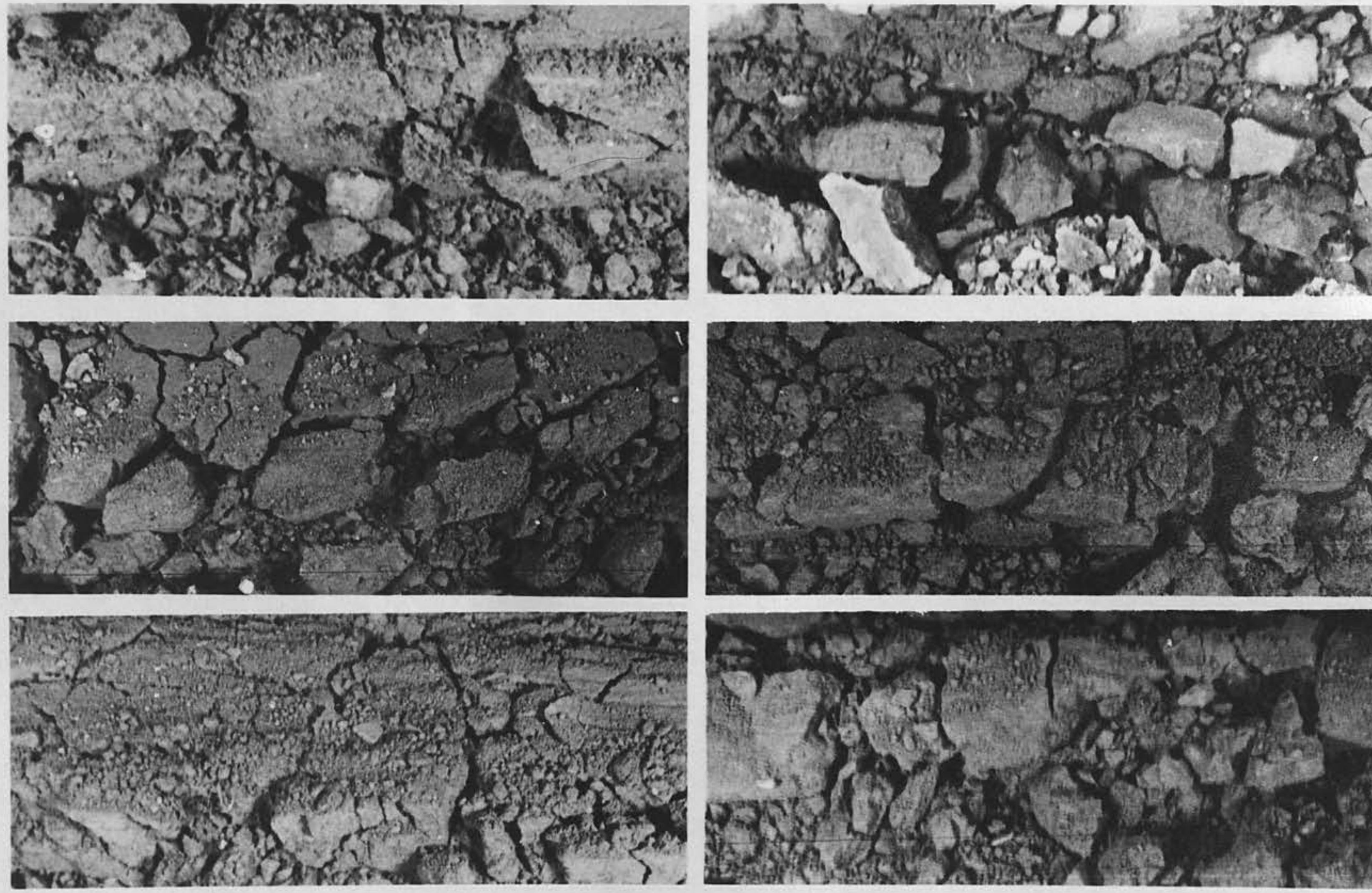


PLATE 20 PULVERIZATION OF THE LESS DENSE BROWN SOIL; HORIZONTAL PLANE OF OSCILLATION, RAKE ANGLE IS 20°,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,
TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

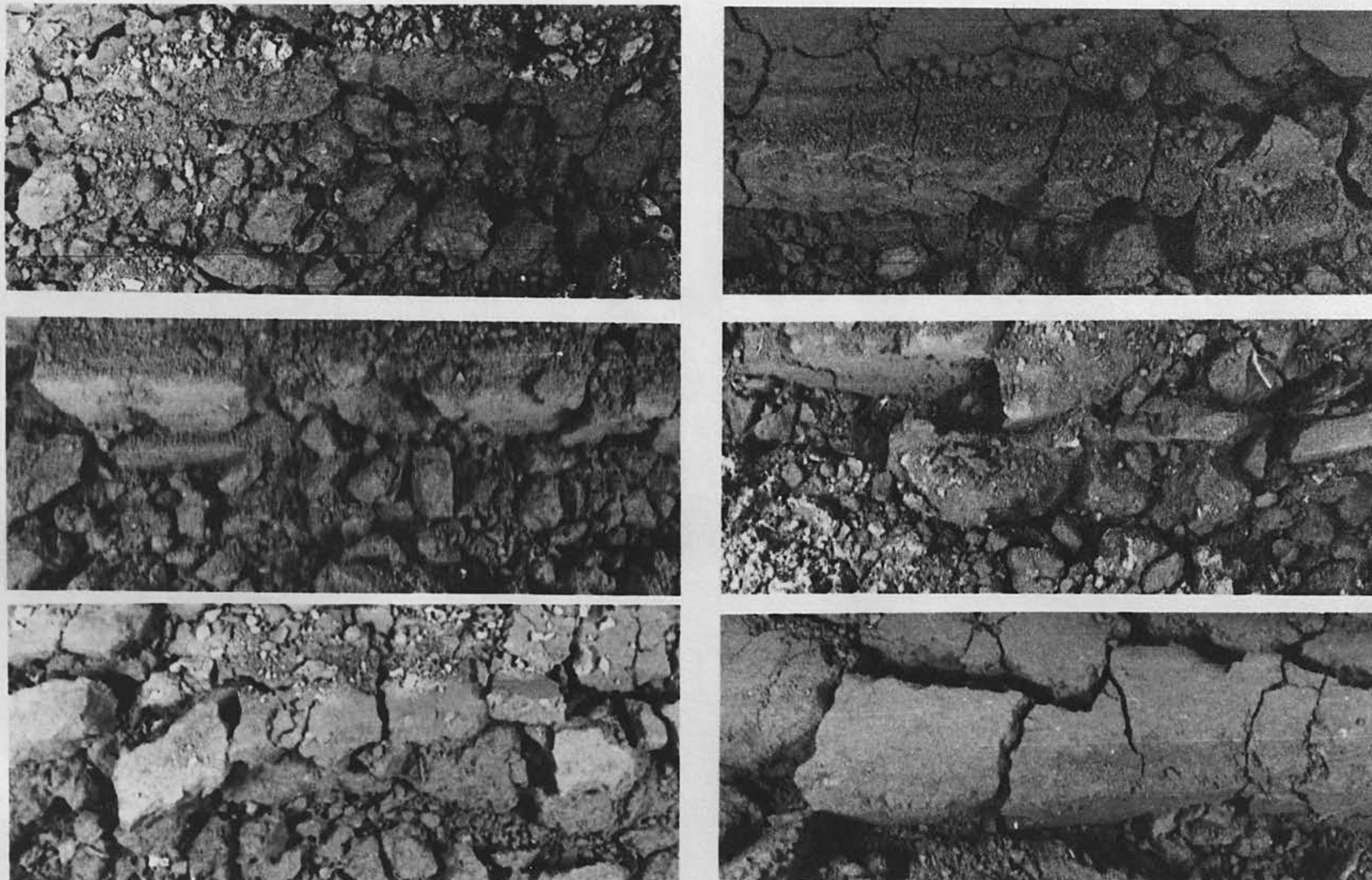


PLATE 21 PULVERIZATION OF THE LESS DENSE BROWN SOIL; TILTED PLANE OF OSCILLATION, RAKE ANGLE IS 20°,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT.
TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

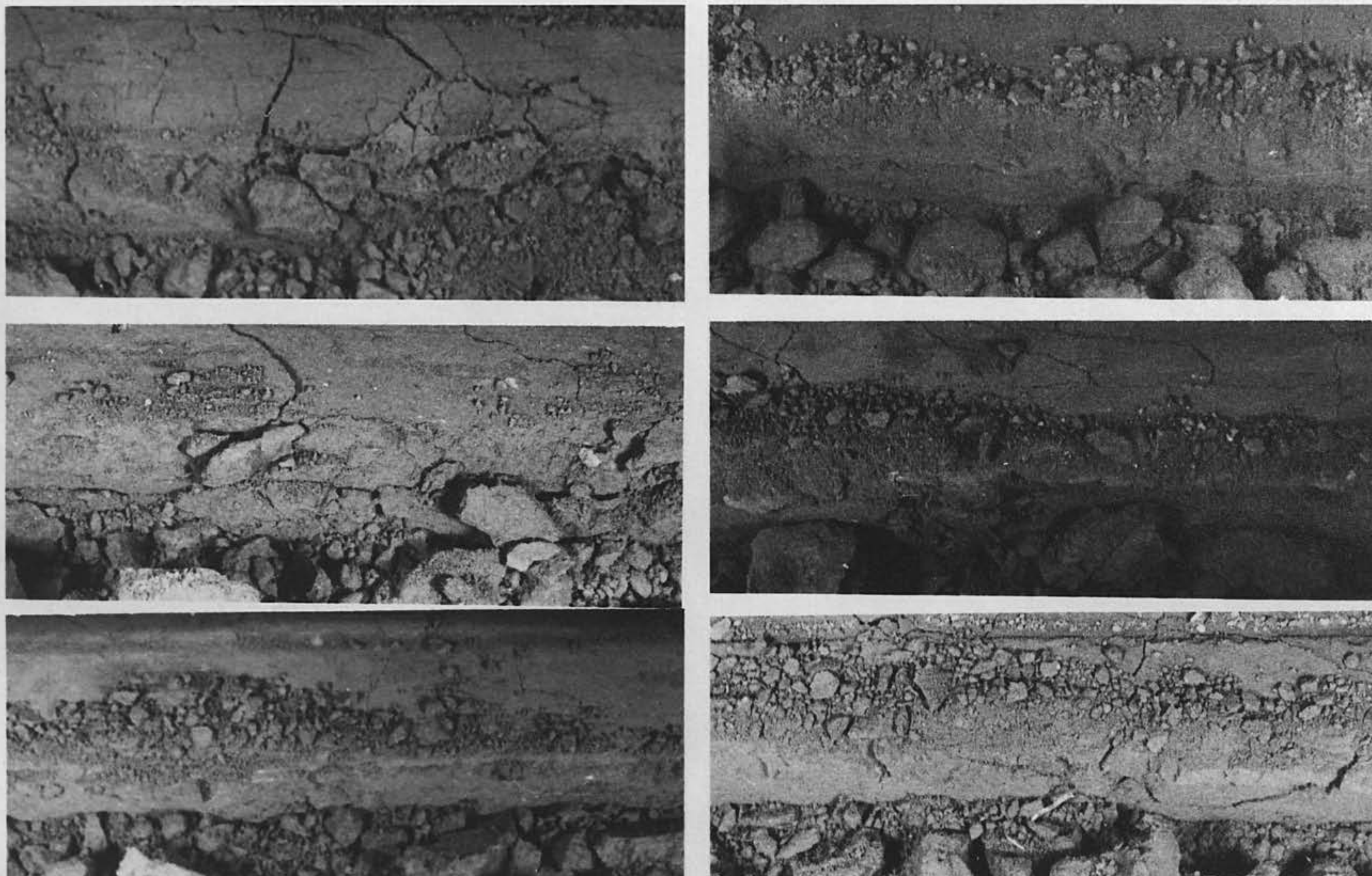


PLATE 22 PULVERIZATION OF THE DENSE BROWN SOIL; HORIZONTAL PLANE OF OSCILLATION, NO RAKE ANGLE,

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,

TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

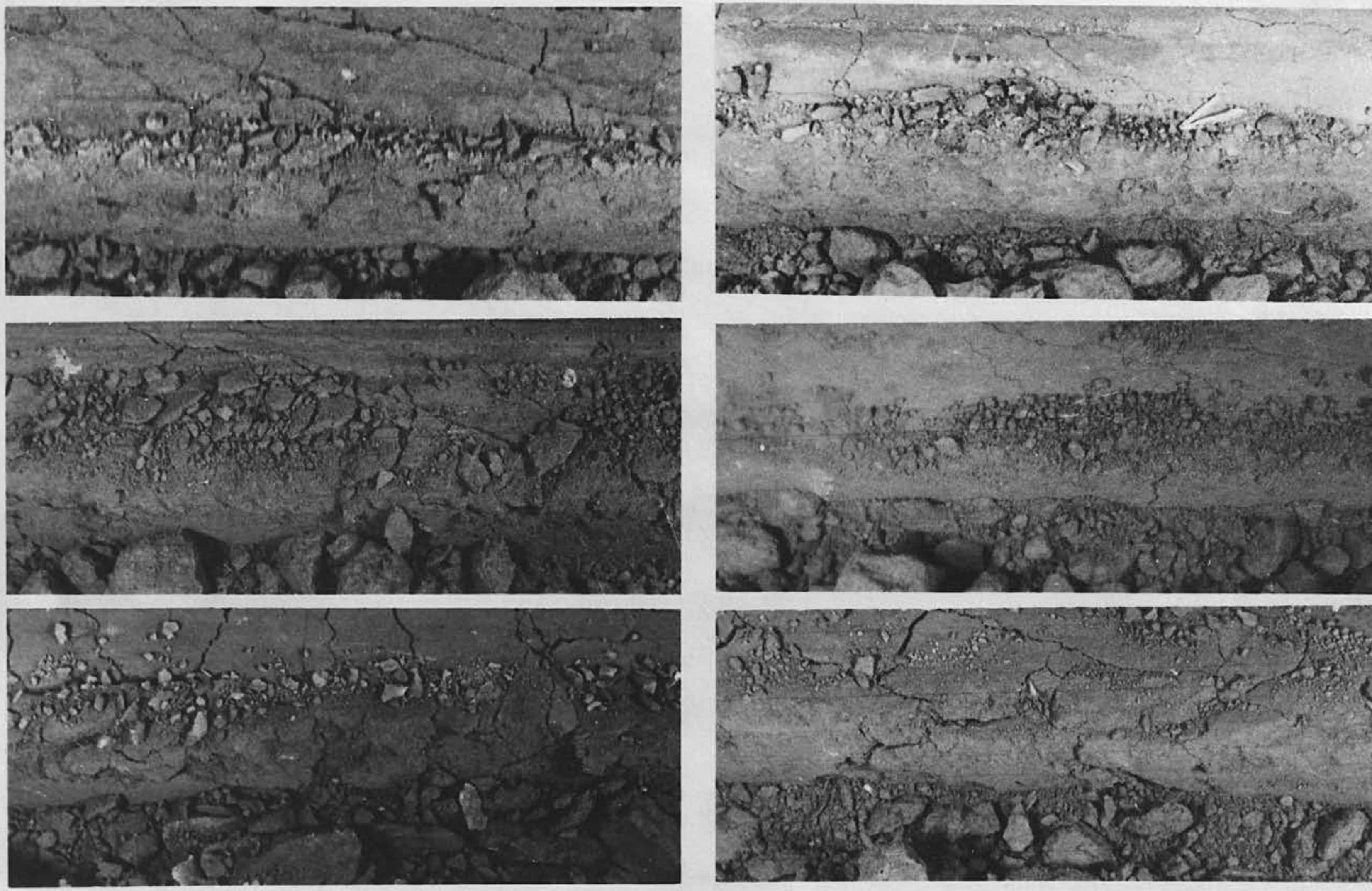


PLATE 23 PULVERIZATION OF THE DENSE BROWN SOIL; TILTED PLANE OF OSCILLATION, NO RAKE ANGLE,

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,

TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

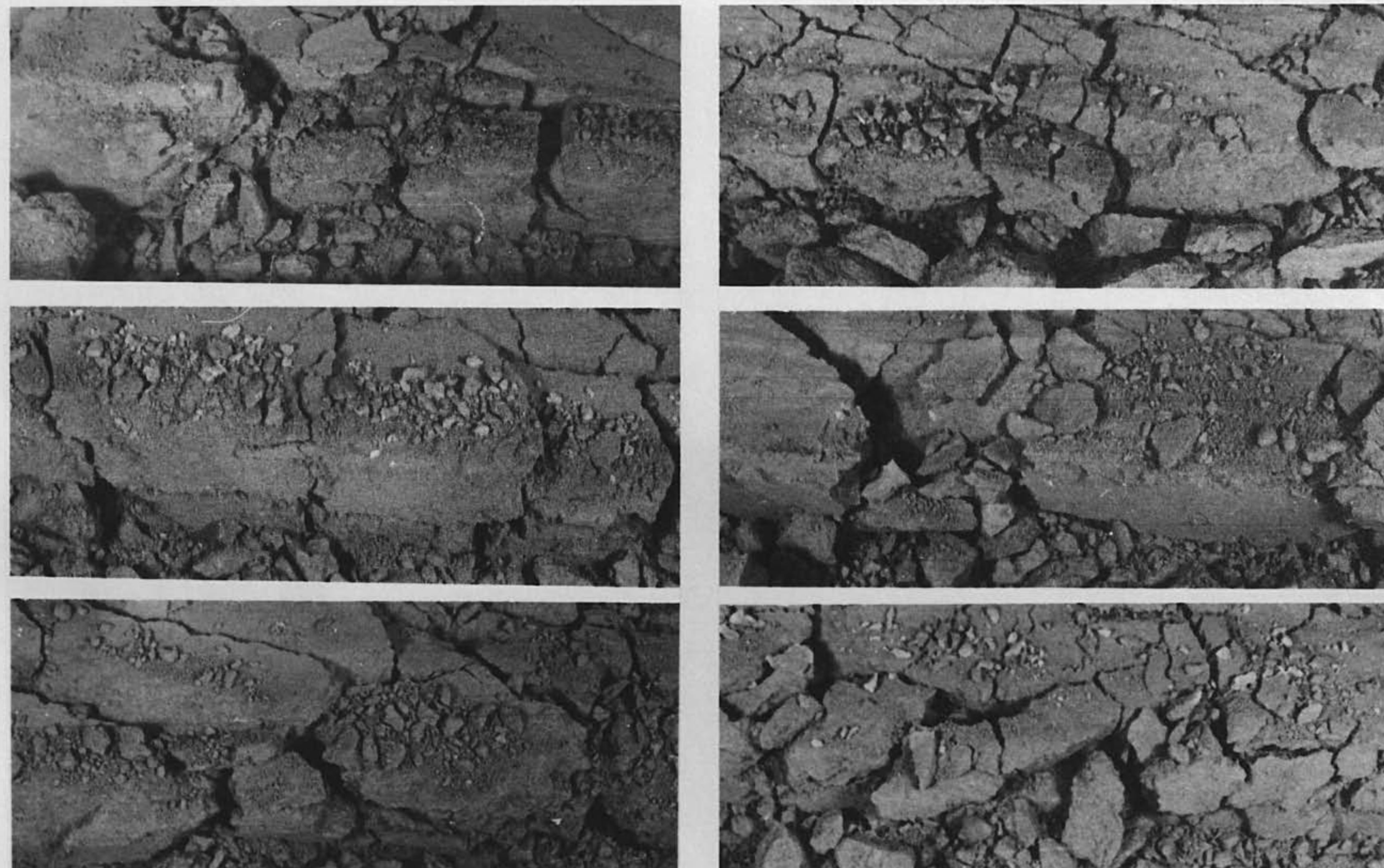


PLATE 24 PULVERIZATION OF THE DENSE BROWN SOIL; HORIZONTAL PLANE OF OSCILLATION, RAKE ANGLE IS 20°,

LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT,

TOP - λ = 6, MID - λ = 4, BTM - λ = 2', TOP - λ = 3, MID - λ = 2, BTM - λ = 1

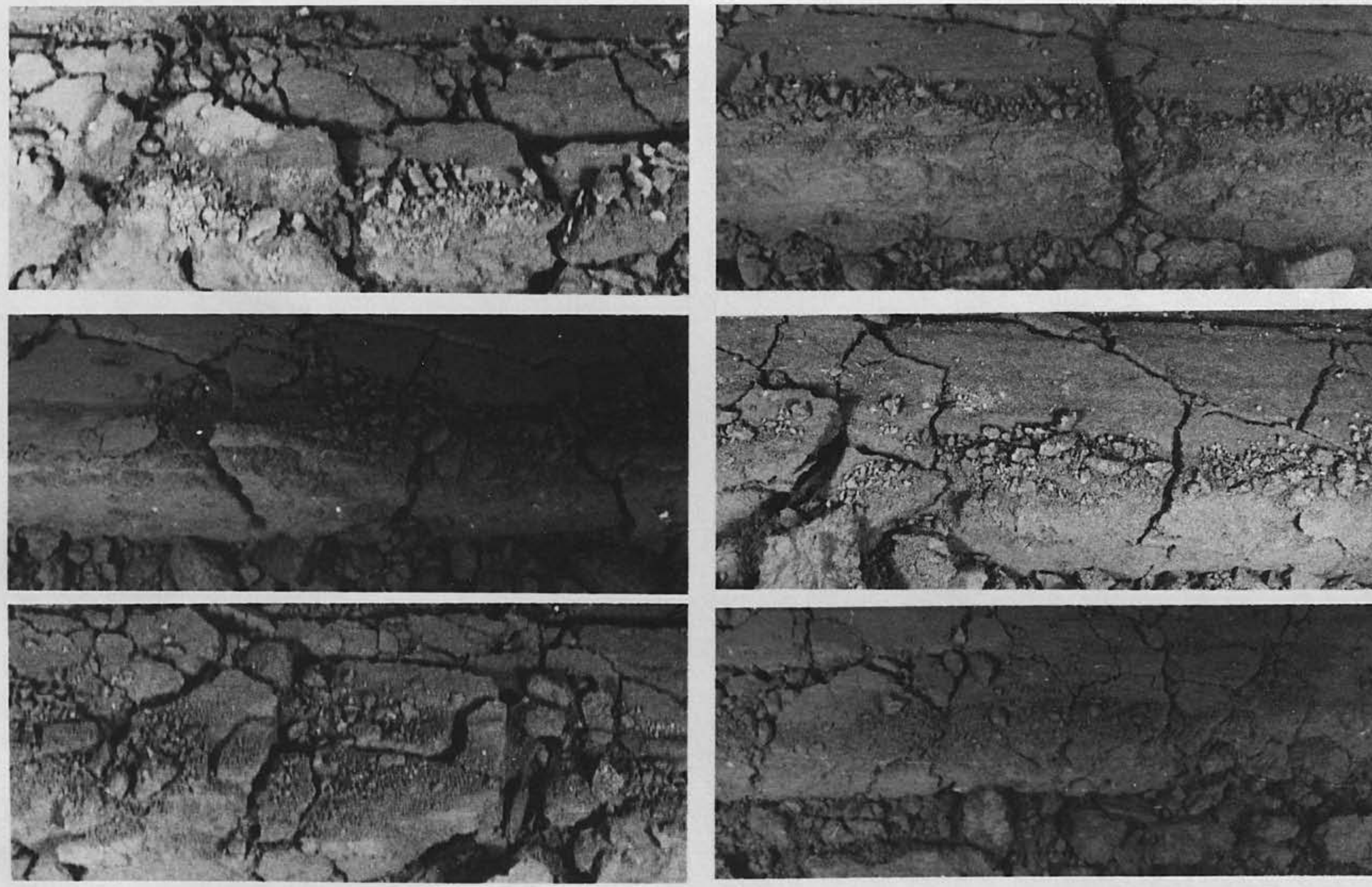


PLATE 25 PULVERIZATION OF THE DENSE BROWN SOIL; TILTED PLANE OF OSCILLATION, RAKE ANGLE IS 20°,
LEFT SIDE - NOMINAL AMPLITUDE = 0.01 FT, TOP - λ = 6, MID - λ = 4, BTM - λ = 2',
RIGHT SIDE - NOMINAL AMPLITUDE = 0.02 FT, TOP - λ = 3, MID - λ = 2, BTM - λ = 1

CHAPTER 10

SUMMARY AND CONCLUSIONS

Introduction

The results of the experiment can be grouped into three categories for the purpose of a summary, depending on whether they confirm, conflict or are outside the experience of other investigators. This method of exposition has merit, in spite of the fallibility of classifying the results, because it assists in clarifying the state of the technology. An additional category regarding experimental techniques is provided which should prove useful in future investigations.

Confirmation of Prior Work

Many of the results obtained confirm those of other investigations. Included in this category are results which conflict, if there was a conflict in the literature. Because of the agreement, the results are not restricted, at least not to the same extent, as are those in the other two categories. The results or observations for this category are;

- there is a reduction in the draught and DHP if the tool is vibrating,
- the draught and DHP are inversely related to the frequency, or are directly related to λ (dimensionless ratio) if the amplitude is constant, with the exception of the minimum frequency-amplitude combination for the dense red soil,
- friction on the underside of the tool, which increases the draught and DHP, occurs when the plane of oscillation is tilted and the rake angle is small,
- the torque and SHP are functions of λ (dimensionless ratio)

and are exceedingly large for reversal of the tool in the soil (λ of 1),

- the minimum draught does not coincide with the minimum THP or energy required,
- with respect to the THP, a vibratory tool is less efficient than a rigid one,
- there appears to be a minimum THP between λ of 1 and 3,
- the dimensional analysis combines the draught and a number of dependent variables into a single equation,
- for dimensional analysis, some soil variable,in addition to the bulk density, is apparently required,
- the size of the clods (soil tilth) is inversely related to the rake angle,
- the size of the clods (soil tilth) is, to a limited extent, directly related to λ (dimensionless ratio).

Confliction with Prior Work

The results of an experiment, which conflict with those of other investigations, are a concern, especially if no argument can be advanced for the difference. The observations for this category are;

- if there is a critical amplitude with respect to the draught and the DHP in less dense soils, it must be either less than 0.01 ft or greater than 0.02 ft,
- there is an increase in the draught and the DHP, which cannot be completely accounted for by friction occurring on the underside of the tool, when the plane of oscillation is tilted for the maximum amplitude (0.02 ft) and which also occurred

for the minimum amplitude (0.01 ft) in the brown soil.

Additional or New Observations

Some of the results obtained appear to be outside the experience of other investigators, particularly with respect to the dependent factor of soil density. The observations for this category are;

- with respect to the draught and DHP, there is an optimum amplitude (minimum draught and DHP) for dense soil which is a function of the frequency,
- the draught and DHP are largely independent of the rake angle for vibratory tillage because a cutter (zero rake angle) of practical dimensions appears to cause considerable strain in the soil,
- the draught and DHP are directly related to the soil density and, to an extent, are a function of the soil type as well, whereas the torque and SHP are independent,
- there is an optimum frequency with respect to the torque and the SHP for the maximum amplitude (0.02 ft); the optimum occurring in the range of 10 to 20 cps,
- a reduction in the torque and SHP occurs for dense soil when the plane of oscillation is tilted, but only at the maximum frequency ($37\frac{1}{2}$ cps),
- the THP is a function of λ (dimensionless ratio) and is exceedingly large for reversal of the tool in the soil (λ of 1),
- a reduction in the THP occurs for less dense soil when the plane of oscillation is tilted and the amplitude is minimum (0.01 ft), but the reverse occurs if the amplitude is maxi-

mum (0.02 ft),

- there is little change in the THP for changes in the soil density and soil type,
- a dimensionless ratio containing the torque could not be obtained because the torque was not a function of the soil density.

Experimental Techniques

It is reasonable to expect that greater bulk densities than the maximum obtained in the experiment can be achieved by using a roller with a larger roller index. The amount of ballast required, however, becomes a problem in itself. Vibratory compaction may be a suitable alternative. If a roller is to be used, pneumatic tyres instead of cast iron wheels would avoid some of the problems with adhesion. It would appear that a density gradient across the tank cannot be avoided and, therefore, the experimental design used, or one similar to it, is required. Manipulation of the soil moisture content, a factor not included in the experiment, is difficult. Perhaps the most practical is to have sufficient soil so that the soil of one moisture content can be replaced with one of a different moisture content. Facilities for storage and rapid handling of the soil would be required for such a system to be practical. Replacing the disk coulters of the furrow plough with powered saw blades (circular) would likely avoid the problems experienced in preparing the soil strips and thereby reduce or eliminate the heterogeneity of the residual variance.

The oscillating mass of the vibratory drive should be counterbalanced, at least if the oscillation is achieved by means of a slider-crank mechanism. Bearing pressures should be low to minimize friction and the linkage should be sufficiently rigid so that the amplitude is not a function of the frequency. In addition, consideration should be given to instrumentation that would directly sense the amplitude.

Conclusions

The basic objective of the investigation was to increase the energy efficiency of the tillage process. It is argued that this objective can be achieved if the cultivating capacity is increased without causing detrimental levels of mechanical impedance in the traffic sole. Vibratory tillage can satisfy these conditions provided the THP of a vibratory tool is not much greater than the DHP of a rigid tool[1]. For tilling dense soil with a rigid tool-implement, the practice is to add ballast to the tractor in order to develop sufficient DHP, but the weight of the ballast increases the mechanical impedance of the traffic sole. Some or all of the ballast can be avoided if a vibratory tool-implement is used for tilling dense soil because the DHP will be reduced. With regard to the THP of a vibratory tool, this approaches the DHP of a rigid tool[1] in a dense soil because the SHP, at least within the limits of the experiment, is independent of the soil density.

An economic appraisal of vibratory tillage cannot be made without experimenting with a full-scale prototype in field conditions. The fixed and operating costs of a vibratory tool-implement were outside the scope of this investigation, as were the differences in the soil resistance between an "in-situ" soil and one that is remoulded. In the design of a prototype, or in further experiments in a soil tank, many of the observations of this investigation and the dimensional analysis should prove useful.

1 In this case the DHP is the THP.

The difference in the response of the DHP and SHP for the soil density may also account for some of the contradictions that appear in the literature. All vibratory tillage studies have noted that the draught of a vibrating tool was less, sometimes substantially less, than the draught of a rigid tool. Some of the studies report a decrease in the total power requirements while others report an increase. It is argued that some of the difference in the THP may have occurred because of differences in the soil density in these studies. Some of the difference in the THP may also be due to the observation that the minimum draught or DHP does not coincide with the minimum energy or THP. In this case there would be a substantial increase in the THP over a rigid tool implement if a large reduction in the draught and DHP was being sought.

It is possible that the reduction in the draught and DHP may be the result of fluidization or thixotrophy of the soil. If the reduction was simply the result of transmitting energy to the soil by some means other than towing the tool, then one would expect the torque and SHP to be a function of the soil density as well as the draught and DHP.

The response of the dependent factors for the two soils was limited and, though that could have been expected on the basis of the particle size distribution, one soil was non-plastic. It was evident in the dimensional analysis that some variable of the soil, in addition to the bulk density, was required. In spite of this limitation, the dimensional analysis did relate the draught with the independent variables of the vibratory drive; frequency and amplitude, the width of the horizontal share and, to an extent, the bulk density of the soil.

One final point. It was evident that the horizontal share with the minimum rake angle caused considerable strain of the soil and, therefore, does not indicate the soil resistance for cutting. Where it might be pragmatic for Barkan (7) to distinguish between "point resistance and skin friction" for driving piles, it does not appear to be so for tillage.

ACKNOWLEDGEMENTS

I wish to thank my two advisors, Mr. K. Simpson of the University of Edinburgh and Dr. I.M. Robertson of the N.I.A.E.-S.S. for their encouragement and frequent advice during the course of this investigation. I am also indebted to Dr. D.P. Blight, Dr. B.D. Soane, Mr. C.A. Carlow and many other members of the staff at Bush. They always exhibited the best in Scottish hospitality, regardless of the problem and the circumstances of the moment. I would like to mention in particular Mr. John Rogerson, who suffered with me through the seemingly endless adjustments required by the factorial experiment.

I appreciated the assistance of Dr. R.M. Cormack, University of Edinburgh and Dr. R. Hardin, University of Alberta for explaining, with much patience on their part, the intricacies of statistical analysis. As for patience, I cannot overlook my two typists, Mrs. Davena Harrison and Miss Elsie Symons who bore the many revisions with grace that is a credit to their gender.

I wish to mention the names of two colleagues at the University of Alberta, Dr. F.V. MacHardy and Mr. J.B. McQuitty. They carried out minor but important roles in this undertaking. In conclusion I thank Jeffrey and Leslie Harrison for their periodic and active participation, and who agreed to part with their friends in Canada while their father furthered his education.

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Table 1-1: Farm Machinery Investment - Alberta, Canada

Type of Machinery	Farm Investment/Cultivated Acre[1] (CDN $)	(% of total)
Power	8.96	38
Cultivation	4.47	19
Haying	1.29	5½
Harvesting	6.87	29
Livestock	0.73	3
Tools and Other	1.21	5½
Total	23.53	100

Table 1-2: Farm Machinery Costs/Cultivated Acre - Alberta, Canada (CDN $)

Agricultural Zones	Fixed Costs[1]	Operating Costs	Total Costs	Total Production Costs[1]	Total Equipment (% of total)
1	2.44	3.21	5.65	18.06	31
2	2.60	3.63	6.23	22.03	28
3	2.98	4.56	7.54	27.15	28
4	2.33	4.29	6.62	17.57	38
5	2.71	4.96	7.67	22.10	35
6	2.98	5.20	8.18	26.98	30
7	2.77	4.76	7.53	21.44	35

1. Alberta Crop Enterprise Analysis - 1966, Publication No. 821/100-1, Alta. Dept. of Agric., Edmonton, Alberta, Canada.

Table 1-3: Harvesting Equipment Cost Schedules[1] - Alberta, Canada (CDN $)

Equipment	Type	Size	Cost per Acre[2]	
Swather	S.P.	12'	1.55	
		16'	1.23	
	P.T.O.	12'	1.13	
		16'	0.94	
Total			4.85	
Mean			1.21	1.21
Combine	P.T.O.	30"	3.57	
		40"	2.83	
	S.P.	30"	3.56	
		34"	4.09	
		43"	3.55	
		45"	3.74	
Total			21.34	
Mean			3.56	3.56
Total of Means				4.77

1 Machine Cost Schedules and Consensus Research Data - 1969, Bulletin 825 - 120/10/69, Alta. Dept. of Agric., Edmonton, Alberta, Canada

2 Includes labor cost.

Table 1-4: Estimate of Cultivation Costs

Agri-cultural Zone	Grain Acres[1] (% of Culti-vated Acres)	Harvesting Cost/Grain Acre (CDN $)	Harvesting Cost/Culti-vated Acre (CDN $)	Cultivation Cost/Culti-vated Acre (CDN $)	Cultivation Cost (% of Total Prod-uction Cost)
1	53.4	4.77	2.54	3.11	17
2	56.6	4.77	2.70	3.53	16
3	60.3	4.77	2.88	4.66	17
4	56.7	4.77	2.71	3.91	22
5	54.7	4.77	2.61	5.06	23
6	64.0	4.77	3.06	5.12	19
7	60.9	4.77	2.91	4.62	22

1 Alberta Crop Enterprise Analysis - 1966, Publication No. 821/100-1, Alta. Dept. of Agric., Edmonton, Alta., Canada.

Table 5-1: Summary of Vibratory Tillage Results [1]

Dimensionless Ratio z'	Draught Reduction %
0.8	60 - 70
1.1	60
1.1	40
1.2	50
1.6	40
1.7	60
1.7	50
2.2	50
3.0	50
4.5	20
6.7	30
7.0	28

1. N.I.A.E. - S.S., Dept. Note No. 45 - D.P. Blight.

Table 5-2: Draught Reduction/Dimensionless Ratio (z') Relationship - Eggenmüller (27)

Velocity (cm/s)	Amplitude (cm)	Frequency (cps) 16	24	32	48
DIMENSIONLESS RATIO - z'					
	0.6	4.2	2.8	2.1	1.4
40	0.9	2.8	1.8	1.4	0.8
	1.2	2.1	1.4	1.0	0.7
	0.6	6.3	4.2	3.1	2.1
60	0.9	4.2	2.8	2.1	1.4
	1.2	3.1	2.1	1.6	1.0
	0.6	8.3	5.5	4.2	2.8
80	0.9	5.5	3.7	2.8	1.8
	1.2	4.2	2.8	2.1	1.4
DRAUGHT REDUCTION (%) - horizontal plane of oscillation					
	0.6	40	50	55	62
40	0.9	30	42	48	62
	1.2	35	48	52	68
	0.6	30	38	45	55
60	0.9	30	38	48	55
	1.2	30	42	52	62
	0.6	20	25	32	45
80	0.9	25	40	48	60
	1.2	30	42	50	60
- tilted plane of oscillation (15°)					
	0.6	50	62	65	72
40	0.9	50	62	65	72
	1.2	50	62	65	72
	0.6	35	45	52	60
60	0.9	38	48	55	65
	1.2	45	55	60	70
	0.6	20	30	40	48
80	0.9	35	45	50	60
	1.2	38	48	55	62

Table 5-3: Average Draught Reduction/Dimensionless Ratio (z') Relationship - Eggenmüller (27)

Dimensionless Ratio z'	Number of Observations	Horizontal Total	Horizontal Mean (%)	Tilted (15°) Total	Tilted (15°) Mean (%)
0.7	1	68	68	72	72
0.8	1	62	62	72	72
1.0	2	114	57	135	68
1.6	1	52	52	60	60
1.8	2	102	51	122	61
2.1	6	285	47	340	56
2.8	6	253	42	306	51
3.1	2	75	38	97	48
3.7	1	40	40	45	45
4.2	5	170	34	211	42
5.5	2	50	25	64	32
6.3	1	30	30	35	35
8.3	1	20	20	20	20

Table 5-4: Power Requirements/Dimensionless Ratio (z') Relationship - Eggenmüller (27)

Dimensionless Ratio z'	Shaft Horsepower
4.2	0.55
3.1	0.55
2.8	0.55
2.1	0.75
1.6	1.00
1.4	1.45
1.0	1.80

Table 7-1: Soil pF/Moisture Content Relationship - Suction and Pressure Head Method.

Soil	γ_D (lb/ft^3)	pF	Moisture Content (% oven dry) 1	2	3	4	5	Mean
		0.0	32.0	33.3	34.0	33.8	32.8	33.2
		1.3	26.6	26.5	26.7	26.8	26.8	26.5
Red	93.4	1.7	23.0	23.0	23.5	23.1	22.7	23.1
		2.0	19.3	19.7	19.7	19.3	18.7	19.5
		3.1	16.4	16.5	17.7	17.8	-	17.1
		0.0	32.1	31.7	31.9	32.5	32.6	32.2
		1.3	25.0	24.7	24.8	24.6	25.1	24.8
Brown	85.8	1.7	20.3	20.3	20.1	20.6	20.5	20.4
		2.0	16.5	16.5	16.3	16.7	16.5	16.5
		3.1	12.0	11.9	12.5	-	-	12.1

Table 7-2: Soil pF/Moisture Content Relationship - Filter Paper Method.

Soil	Soil Moisture (% oven dry)	Paper Position	Final Weight Paper	Initial Weight Paper	Water (grams)	Paper Moisture (oven dry)	pF
		btm	.511	.380			
	12.6	top	.525	.382			
		mean	.518	.381	.137	36.0	3.5
		btm	.453	.386			
	7.6	top	.435	.369			
Red		mean	.444	.378	.066	17.4	5.0
		btm	.450	.380			
	7.7	top	.440	.375			
		mean	.445	.378	.067	17.7	4.9
		btm	.411	.367			
	5.8	top	.413	.362			
		mean	.412	.364	.048	13.2	5.3
		btm	.516	.370			
	13.4	top	.552	.365			
		mean	.539	.368	.171	46.5	3.0
		btm	.464	.370			
	7.2	top	.455	.364			
Brown		mean	.460	.367	.093	25.3	4.3
		btm	.404	.357			
	3.9	top	.414	.360			
		mean	.409	.358	.051	14.2	5.2
		btm	.442	.363			
	6.4	top	.455	.372			
		mean	.448	.368	.080	21.8	4.6

Table 7-3: Soil Texture Analysis - Red and Brown Soils.

Soil Type	Lower Size (mm)	Percentage Retained Sample 1	Sample 2	Mean	Cumulative Percentage Retained	Passing
Red	37.5	0	0	0	0	100.0
	20.0	0	0	0	0	100.0
	10.0	0	0	0	0	100.0
	5.00	1.0	1.0	1.0	1.0	99.0
	2.00	1.0	1.1	1.1	2.1	97.9
	0.60	2.9	3.0	2.9	5.1	94.9
	0.20	11.8	12.0	11.9	17.0	83.0
	0.06	34.7	34.2	34.4	51.4	48.6
	0.02	22.0	21.6	21.8	73.2	26.8
	0.006	5.8	6.9	6.3	79.6	20.4
	0.002	5.3	4.6	4.9	84.5	15.5
	0.000	15.4	15.6	15.5	100.0	0.0
Brown	37.5	0.0	0.0	0.0	0.0	100.0
	20.0	0.0	0.0	0.0	0.0	100.0
	10.0	0.0	0.0	0.0	0.0	100.0
	5.00	1.1	1.1	1.1	1.1	98.9
	2.00	0.9	0.9	0.9	2.0	98.0
	0.60	1.9	1.8	1.8	3.9	96.1
	0.20	16.3	15.6	16.0	19.9	80.1
	0.06	55.1	54.3	54.7	74.5	25.5
	0.02	9.4	11.6	10.5	85.0	15.0
	0.006	4.1	2.6	3.3	88.4	11.6
	0.002	2.9	3.4	3.1	91.5	8.5
	0.000	8.2	8.7	8.5	100.0	0.0

Table 7-4: Soil Moisture Content at Appropriate Stages of Moisture Manipulation[1]

		Weight (grams)					Percentage	
Soil	Sample	Wet Soil and Container	Dry Soil and Container	Container	Dry Soil	Moisture	Moisture	Mean
On Receipt (Nov. 5/69)								
	1	209.0	195.8	74.5	121.3	13.2	10.9	
Red	2	210.0	196.2	74.5	121.7	13.8	11.3	
	3	209.0	194.8	74.4	120.4	14.2	11.8	11.0
	1	173.0	159.8	74.8	85.0	13.2	15.5	
Brown	2	177.0	163.0	73.8	89.2	14.0	15.7	
	3	175.0	161.8	74.3	87.5	13.6	15.5	15.6
After Drying Brown and Wetting Red Soil (Feb. 9/70)								
	1	418.6	372.4	74.8	297.6	46.2	15.5	
Red	2	390.0	348.5	73.8	274.7	41.5	15.1	
	3	426.2	380.7	73.6	307.1	45.5	14.8	
	4	391.7	350.5	74.0	276.5	41.2	14.9	15.1
	1	359.5	331.1	74.3	256.8	28.4	11.1	
Brown	2	369.5	337.9	74.5	263.4	31.6	11.2	
	3	391.0	356.1	74.5	281.6	34.9	11.2	
	4	344.0	317.6	74.4	243.2	26.4	11.1	11.2
Near Completion of Tillage Experiments (June 26/70)								
	1	192.2	177.4	73.6	N/A	N/A	14.3	
	2	177.7	164.6	74.0	N/A	N/A	14.5	
Red	3	149.8	140.0	75.0	N/A	N/A	15.1	
	4	94.7	92.0	74.1	N/A	N/A	15.1	
	5	102.7	98.9	74.3	N/A	N/A	15.4	14.9
	1	95.9	93.7	74.2	N/A	N/A	11.3	
	2	102.9	100.1	73.4	N/A	N/A	10.5	
Brown	3	87.8	86.5	75.2	N/A	N/A	11.5	
	4	102.5	99.3	75.1	N/A	N/A	13.2	
	5	89.9	88.2	72.8	N/A	N/A	11.0	11.5

1 Many other tests (of limited sample number) were made, particularly in bringing the two soils to an equal pF.

Table 7-5: Compaction Tests[1] - Dry Density/Moisture Content Relationship

BRITISH STANDARD COMPACTION TEST - A.A.S.H.O. T.99-38

Soil	Red						Brown				
Sample Number	1	2	3	4	5	6	1	2	3	4	5
Wet Soil, Mould	5464	5665	5672	5633	5479	5244	5649	5650	5604	5563	5599
Wet Soil	1705	1906	1913	1874	1720	1485	1890	1891	1845	1804	1840
γ_W (lb/ft^3)	112.9	126.0	126.7	124.0	113.4	98.0	124.7	124.7	122.2	119.1	121.7
Wet Soil, Can	55.99	62.88	58.96	56.00	70.27	53.40	63.12	58.70	65.08	48.82	69.02
Dry Soil, Can	53.32	58.47	54.48	51.20	62.03	52.16	58.15	53.43	58.38	46.22	61.80
Can	27.63	28.03	28.30	27.59	27.31	27.19	27.19	26.49	26.97	26.94	27.15
Water	2.67	4.41	4.48	4.80	8.24	1.24	4.97	5.27	6.70	2.60	7.22
Dry Soil	25.69	30.44	26.18	23.61	34.72	24.97	30.96	26.94	31.41	19.28	34.65
Water (%)	10.4	14.5	17.1	20.3	23.7	4.98	16.1	19.6	21.3	13.5	20.8
γ_D (lb/ft^3)	102	110	108	103	91.5	93.5	107	104	101	105	101

Continued

1 except where noted, all weights are in grams, mould weighs 3759 grams.

Table 7-5: Continued

MODIFIED STANDARD COMPACTION TEST

Soil	Red					Brown				
Sample Number	1	2	3	4	5	1	2	3	4	5
Wet Soil, Mould	5742	5692	5624	5554	5621	5697	5631	5544	5516	5656
Wet Soil	1983	1933	1865	1795	1892	1938	1872	1785	1757	1897
γ_w(lb/ft^3)	131.2	127.8	123.4	118.8	125.2	128.1	123.8	118.0	116.2	125.4
Wet Soil, Can	45.78	54.55	53.94	49.11	54.45	54.06	52.83	65.07	55.83	44.78
Dry Soil, Can	43.38	50.66	51.48	47.41	50.20	50.38	48.86	58.25	53.91	43.02
Can	26.91	27.57	27.63	28.30	28.03	27.78	27.40	27.98	27.15	26.86
Water	2.04	3.89	2.46	1.70	4.25	3.69	3.97	6.82	1.92	1.76
Dry Soil	16.47	23.09	23.85	19.11	22.17	22.60	21.46	30.27	26.75	16.16
Water (%)	14.6	16.8	10.3	8.9	19.2	16.3	18.4	22.5	7.2	10.9
γ_D (lb/ft^3)	114.6	109.5	112.0	109.0	105.0	110.1	104.5	96.3	108.3	113.0

Continued

Table 7-5: Continued

SPECIAL COMPACTION TEST (standard/ 2)

Soil	Red						Brown				
Sample Number	1	2	3	4	5	6	1	2	3	4	5
Wet Soil,	5381	5497	5574	5594	5562	5523	5553	5605	5577	5529	5394
Wet Soil	1622	1738	1815	1835	1803	1764	1794	1846	1818	1770	1635
γ_W (lb/ft^3)	107.3	115.0	120.1	121.5	119.3	116.8	118.5	122.2	120.5	117.2	108.0
Wet Soil, Can	41.30	46.36	56.68	56.47	57.90	62.64	45.39	56.37	58.68	68.80	47.70
Dry Soil, Can	39.89	43.84	52.42	51.58	52.13	55.39	42.96	51.62	52.92	60.05	45.62
Can	27.40	27.00	27.28	27.12	27.28	26.99	27.59	27.31	27.19	27.19	26.49
Water	1.41	2.52	4.26	4.89	5.77	7.25	2.43	4.75	5.76	8.75	2.08
Dry Soil	12.49	16.84	25.14	24.46	24.85	28.40	15.37	24.31	25.73	32.86	19.13
Water (%)	11.3	15.0	17.0	20.0	23.2	25.5	15.8	19.6	22.4	26.6	10.9
γ_D(lb/ft^3)	94.3	99.8	102.5	101.1	96.7	92.5	102.3	102.3	98.6	92.4	97.3

Table 7-6: Soil Density (time for 10,000 counts)/No. of Roller Passes Relationship - Roller Index = 18.

Position In Tank down	across	Depth in Tank (in) 1	3	5	7	9	T_S(sec)
		T_T(sec)					
RED SOIL (moisture content = 15%)							
	a	65.5	61.1	61.4	65.7	63.0	53.0
1	b	66.9	58.3	58.7	62.0	61.3	53.4
	c	59.5	55.8	57.5	56.0	57.0	52.5
	a	62.0	60.7	63.7	62.5	69.7	52.5
2	b	64.1	59.2	60.0	61.6	67.7	52.6
	c	61.2	57.2	59.1	60.1	62.8	53.0
	a	62.2	60.8	62.9	64.0	69.3	53.7
3	b	64.3	59.0	60.0	59.5	64.7	53.6
	c	61.7	57.0	57.4	58.2	64.8	52.5
	a	64.5	61.8	64.8	63.8	67.2	52.6
4	b	63.8	59.7	61.2	62.5	64.6	52.3
	c	60.6	57.4	57.3	54.8	64.0	53.4
Mean		63.0	59.0	60.3	60.9	64.7	52.9
T_T/T_S		1.19	1.12	1.14	1.15	1.22	
$\gamma_W(lb/ft^3)$		99.8	91.0	93.1	94.8	103.0	
$\gamma_D(lb/ft^3)$		86.8	79.1	81.0	82.5	89.6	
BROWN SOIL (moisture content = 11.2%)							
	a	59.7	58.0	60.9	60.1	57.9	53.0
1	b	59.5	64.0	61.0	58.5	59.4	51.9
	c	59.7	57.0	60.2	58.4	59.4	53.1
	a	60.4	57.0	60.9	60.2	60.3	53.1
2	b	59.5	58.2	56.5	58.7	57.7	53.0
	c	63.8	56.9	57.5	56.8	56.6	53.1
	a	62.0	60.4	62.5	63.2	62.2	53.1
3	b	61.4	57.5	56.4	57.0	55.8	53.1
	d	62.0	58.5	57.5	57.5	57.5	53.4
	a	58.7	56.1	60.5	62.0	60.6	53.4
4	b	60.1	57.5	57.7	58.8	57.0	52.4
	c	59.2	55.1	57.5	60.0	60.1	52.4
Mean		60.5	58.0	59.1	59.2	58.7	52.9
T_T/T_S		1.14	1.10	1.12	1.12	1.11	
$\gamma_W(lb/ft^3)$		93.1	87.3	91.0	91.0	88.5	
$\gamma_D(lb/ft^3)$		83.0	77.7	81.0	81.0	78.8	

Table 7-7: Soil Density (time for 10,000 counts)/No. of Roller Passes Relationship - Roller Index = 45.

RED SOIL (moisture content = 15.1%)

Position in Tank down	across	Depth in Tank[1] (in.) 1 T_T(sec)	3	T_S(sec)
1	b	60.5	59.2	53.1
2	b	61.2	61.5	52.9
3	b	64.2	61.4	52.5
4	b	62.4	62.0	51.7
Mean		62.1	61.0	52.6
T_T/T_S		1.18	1.16	
γ_W(lb/ft^3)		98.6	96.0	
γ_D(lb/ft^3)		85.6	83.5	

BROWN SOIL (moisture content = 11.2%)

Position in Tank down	across	Depth 1 T_T(sec)	3	T_S(sec)
1	b	60.5	60.0	52.5
2	b	59.0	56.0	51.7
3	b	60.2	58.5	53.1
4	b	61.5	59.7	52.6
Mean		60.3	58.6	52.5
T_T/T_S		1.15	1.12	
γ_W(lb/ft^3)		94.8	91.8	
γ_D(lb/ft^3)		85.3	82.7	

1 not including 2 inches of soil cover.

Table 7-8: Soil Density/Compaction Procedure Relationship - Depth = 3 in.

Soil		Red		Brown	
Roller Index		18	60	18	60
Number of Passes		5	15	10	15
Position in Tank down	across	Less Dense	Dense	Less Dense	Dense
		γ_D (lb/ft^3 - dry)			
	a	67.1	62.8	71.9	86.5
	b	80.2	93.0	64.3	84.0
1	c	69.7	91.1	62.4	88.7
	d	62.1	90.5	69.7	85.3
	e	60.5	81.9	56.6	70.9
	a	61.3	73.9	55.6	77.0
	b	60.2	83.5	66.1	83.7
2	c	70.4	94.6	71.4	84.2
	d	66.7	89.0	65.1	85.7
	e	58.5	85.3	67.0	79.8
	a	70.2	84.1	64.4	59.2
	b	61.2	92.1	65.5	79.3
3	c	64.9	91.3	64.4	81.7
	d	48.9	91.8	61.1	82.2
	e	58.5	77.5	44.9	74.5
Mean		64.0	85.5	63.4	80.2

Table 7-9: Soil Resistance of a Cone Penetrometer[1]/Compaction Procedure Relationship - Depth = 3 in.

Soil		Red				Brown			
Roller Index		18		60		18		60	
Number of Passes		5		15		10		15	
Position in Tank									
down	across	Less Dense		Dense		Less Dense		Dense	
		CBR	CR	CBR	CR	CBR	CR	CBR	CR
	b	0.8	81	4.4	308	1.0	99	8.0	453
	b/	0.9	90	6.2	383	0.9	90	6.6	400
	mean		86		345		94		426
	c	0.9	90	7.5	435	1.0	99	10.0	525
1	c/	0.6	62	10.0	525	1.1	107	8.5	472
	mean		76		480		103		498
	d	1.2	115	5.0	334	1.4	130	5.2	343
	d/	1.1	107	5.1	338	1.0	99	8.1	458
	mean		111		336		114		400
	b	0.7	72	9.2	495	1.4	130	7.0	415
	b/	0.8	81	10.0	525	0.8	81	6.0	377
	mean		76		510		106		396
	c	0.8	81	7.9	450	1.1	107	9.3	500
2	c/	0.8	81	8.2	462	1.7	152	10.0	525
	mean		81		456		130		512
	d	1.0	99	5.0	334	1.6	145	6.2	383
	d/	0.9	90	6.1	380	1.2	115	8.5	472
	mean		94		357		130		427
	b	1.2	115	9.6	512	0.9	90	7.2	423
	b/	1.0	99	8.2	462	1.0	99	7.6	438
	mean		107		487		94		430
	c	1.1	107	7.4	432	1.3	122	6.9	412
3	c/	1.2	115	7.6	438	1.2	115	10.0	525
	mean		111		435		118		468
	d	0.9	90	5.9	373	1.2	115	6.3	388
	d/	1.0	99	7.5	435	1.1	107	6.6	400
	mean		94		404		111		394

1 Dimensions per Amer. Soc. Agr. Engin. - R313,

CBR - California Bearing Ratio, %,

CR - Cone Resistance (0.2 sq. in), psi,

CBR - CR for Farnell Model 244 Penetrometer per N.I.A.E.-S.S.

Table 9-1: Part 1 Results - Less Dense Red Soil

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	8	3.7	293.6	93.0	6.46	7.35	6.93	3.20	3.21	2.58	34.5	37.5	35.8
1	b	8	50.6	111.1	89.9	6.97	7.62	7.37	2.83	2.83	2.78	33.9	36.9	35.1
	c	9	41.7	114.5	86.7	7.51	8.16	7.88	2.81	2.80	2.80	33.6	36.3	34.6
	a	6	60.0	208.4	125.7	0.00	0.00	0.00	2.62	2.53	2.74	00.0	00.0	00.0
2	b	8	22.9	77.9	61.9	6.41	6.65	6.52	2.65	2.65	2.76	37.2	37.8	37.5
	c	8	14.0	174.7	88.5	3.00	3.25	3.12	2.67	2.68	2.68	40.5	40.8	40.7
	a	7	62.1	196.7	138.8	0.00	0.00	0.00	3.12	3.01	2.78	00.0	00.0	00.0
3	b	9	2.75	155.3	70.5	6.37	6.96	6.63	2.27	2.25	2.66	36.9	37.2	37.1
	c	6	34.8	159.8	91.8	2.16	2.57	2.28	2.83	2.83	2.87	40.5	40.5	40.5
	a	7	34.4	127.8	63.2	7.68	8.39	8.02	2.56	2.53	2.68	35.4	36.3	35.8
4	b	7	1.37	142.9	59.1	7.91	8.62	8.32	2.17	2.19	2.67	35.4	36.6	35.8
	c	8	38.5	86.6	60.1	7.24	9.13	8.27	2.76	2.75	2.66	35.1	36.3	35.7
	a	8	41.2	252.8	152.5	0.00	0.00	0.00	3.15	2.96	2.82	00.0	00.0	00.0
1	b	7	34.8	76.0	54.4	10.31	10.84	10.62	2.82	2.86	2.75	32.4	32.7	32.5
	c	8	26.6	150.2	83.9	4.66	4.84	4.71	2.45	2.56	2.68	39.3	40.8	40.1
	a	6	60.2	238.8	122.3	9.18	10.36	9.50	2.78	2.66	2.79	33.3	35.1	33.8
2	b	6	86.3	112.4	103.5	9.03	10.33	9.60	2.75	2.86	2.83	27.3	28.5	28.0
	c	8	71.2	123.4	99.9	7.05	7.47	7.30	2.73	2.72	2.75	36.3	36.9	36.4
	a	9	43.8	171.5	97.2	7.00	7.54	7.23	2.82	2.80	2.76	36.3	36.6	36.5
3	b	7	43.5	126.0	91.4	6.74	7.74	7.47	2.72	2.74	2.73	36.3	36.9	36.6
	c	8	89.8	136.5	111.2	7.48	7.77	7.67	2.78	2.74	2.67	36.0	36.9	36.4
	a	7	94.1	198.5	149.5	0.00	0.00	0.00	2.93	2.90	2.75	00.0	00.0	00.0
4	b	8	15.1	112.7	57.5	7.72	8.31	8.04	3.04	2.98	2.88	33.3	33.9	33.5
	c	7	39.8	171.8	103.2	4.82	5.70	5.29	2.89	2.96	2.82	38.7	39.6	39.1

Table 9-2: Part 1 Results - Dense Red Soil

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	7	22.0	259.7	123.5	9.01	9.84	9.06	2.54	2.51	2.60	36.9	36.6	36.8
1	b	5	19.2	482.3	194.6	8.94	9.41	9.18	2.40	2.41	2.95	36.0	36.6	36.2
	c	6	35.7	189.6	130.1	9.08	10.03	9.64	2.70	2.69	2.74	35.7	36.3	36.0
	a	6	491.4	595.0	543.0	0.00	0.00	0.00	2.65	2.68	2.51	00.0	00.0	00.0
2	b	6	374.0	552.1	467.2	9.9	11.4	10.5	2.67	2.57	2.61	36.0	37.2	36.6
	c	6	176.8	593.1	33.50	4.61	5.91	5.41	2.77	2.68	2.52	38.7	41.7	39.9
	a	6	559.4	725.7	656.3	0.00	0.00	0.00	2.57	2.45	2.49	00.0	00.0	00.0
3	b	4	417.7	538.6	447.9	10.95	12.55	11.65	2.61	2.68	2.75	Missing		34.2
	c	8	429.1	584 4	483.4	6.72	7.19	6.98	2.44	2.29	2.55	Missing		38.6
	a	7	156.6	333.9	279.7	9.99	12.11	10.84	2.48	2.63	2.57	Missing		35.0
4	b	8	238.6	351.3	297.5	10.05	12.00	11.1	2.69	2.60	2.63	Missing		34.9
	c	7	202.0	365.5	297.2	10.91	12.10	11.35	2.93	2.95	2.75	Missing		34.5
	a	6	491.2	781.2	652.4	0.00	0.00	0.00	2.92	2.78	2.59	00.0	00.0	00.0
1	b	5	358.6	485.0	414.7	10.34	11.29	10.68	2.40	2.39	2.47	36.0	36.3	36.1
	c	9	425.2	592.9	479.6	5.73	6.44	5.99	2.32	2.37	2.53	39.6	40.8	40.0
	a	9	255.3	619.4	407.8	8.94	10.30	9.48	1.88	1.79	1.82	36.0	36.9	36.5
2	b	5	390.4	530.6	468.5	9.12	9.89	9.44	2.24	2.22	2.17	35.7	38.1	36.7
	c	5	151.8	249.4	209.8	8.47	9.83	9.32	2.81	2.79	2.74	36.6	36.9	36.7
	a	6	130.8	437.2	351.0	10.02	11.20	10.54	2.49	2.60	2.56	35.4	37.2	36.2
3	b	5	308.9	376.2	343.8	9.25	12.68	11.28	2.45	2.58	2.62	35.7	37.2	36.4
	c	7	318.1	408.8	357.5	11.02	12.32	11.49	2.63	2.65	2.69	35.7	36.6	36.2
	a	3	284.4	357.2	320.6	0.00	0.00	0.00	2.77	2.75	2.77	00.0	00.0	00.0
4	b	2	152.7	184.3	168.5	9.57	10.87	10.22	2.71	2.90	2.80	34.5	33.0	33.8
	c	5	92.7	275.5	206.8	4.34	6.06	5.02	2.88	2.92	2.78	38.7	39.6	39.0

Table 9-3: Part 1 Results - Less Dense Brown Soil

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	6	51.7	153.4	104.9	7.17	7.70	7.47	2.81	2.92	2.76	33.6	34.5	33.9
1	b	6	69.8	122.1	85.6	8.27	8.75	8.46	2.91	2.90	2.94	33.3	33.6	33.4
	c	3	56.1	80.8	71.7	6.90	7.55	7.28	2.76	2.85	2.81	33.3	33.9	33.7
	a	8	85.9	216.4	159.4	0.00	0.00	0.00	3.11	3.04	2.88	0.00	0.00	0.00
2	b	7	86.8	110.1	98.8	2.25	6.55	6.43	2.79	2.79	2.82	36.9	37.8	37.3
	c	6	30.9	219.1	126.0	2.40	3.29	3.03	2.78	2.84	2.75	40.2	40.8	40.4
	a	9	73.7	262.0	163.2	0.00	0.00	0.00	2.72	2.85	2.79	0.00	0.00	0.00
3	b	8	50.1	127.1	86.4	6.79	7.14	7.00	2.77	2.72	2.73	36.3	36.9	36.5
	c	4	14.4	206.8	97.9	2.01	2.66	2.44	2.68	2.69	2.60	40.5	40.5	40.5
	a	5	7.3	95.3	52.1	8.16	9.34	8.82	2.59	2.63	2.67	35.4	36.0	35.8
4	b	9	13.0	128.5	54.3	7.30	9.01	8.26	2.95	2.93	2.71	35.1	35.7	35.4
	c	6	27.5	105.8	67.3	7.62	8.57	8.16	2.99	2.89	2.76	34.2	35.7	34.8
	a	8	14.7	278.5	125.3	0.00	0.00	0.00	2.79	2.88	2.71	0.00	0.00	0.00
1	b	9	25.0	112.9	65.6	10.86	11.39	11.09	2.65	2.68	2.69	30.6	31.8	31.2
	c	8	29.8	130.1	96.6	7.93	9.41	8.79	2.74	2.73	2.72	36.0	37.8	36.6
	a	9	14.1	153.2	69.5	6.73	8.03	7.33	2.75	2.80	2.68	36.0	37.2	36.6
2	b	6	49.7	123.9	95.7	7.73	7.85	7.79	2.79	2.81	2.70	36.0	36.9	36.4
	c	9	2.3	161.7	103.8	7.86	8.45	8.08	2.57	2.57	2.71	36.0	36.9	36.4
	a	9	10.8	183.9	74.0	4.62	7.58	5.75	2.84	2.86	2.68	36.6	37.5	37.0
3	b	6	90.0	153.2	127.6	8.38	9.15	8.80	2.71	2.71	2.73	36.3	37.8	36.8
	c	6	90.0	158.7	125.5	8.09	9.80	8.79	2.81	2.74	2.72	35.7	36.6	36.4
	a	6	94.3	367.8	183.7	0.00	0.00	0.00	2.73	2.43	2.78	0.00	0.00	0.00
4	b	7	37.1	126.4	75.0	8.30	8.95	8.65	2.90	2.90	2.80	34.2	34.8	34.5
	c	8	34.1	193.5	123.6	4.17	4.58	4.31	2.86	2.84	2.83	39.3	40.2	39.6

Table 9-4: Part 1 Results - Dense Brown Soil.

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	9	74.9	340.1	157.0	8.88	10.23	9.82	2.59	2.48	2.83	34.5	37.2	35.8
1	b	7	105.3	117.7	109.9	10.65	11.24	10.87	2.89	2.83	2.87	34.8	36.0	35.4
	c	6	84.5	290.6	166.3	10.24	11.60	11.06	2.72	2.75	2.84	34.2	35.1	34.6
	a	8	232.7	765.8	459.4	0.00	0.00	0.00	2.93	2.92	2.77	0.00	0.00	0.00
2	b	9	221.9	410.2	282.8	9.10	11.29	10.09	2.70	2.65	2.75	Missing		35.7
	c	6	77.8	345.7	263.3	4.18	6.08	5.34	2.94	2.95	2.90	Missing		40.4
	a	7	321.5	480.9	402.0	0.00	0.00	0.00	2.99	2.84	2.81	0.00	0.00	0.00
3	b	5	160.6	243.0	203.7	9.15	10.63	9.68	2.77	2.70	2.69	Missing		36.1
	c	7	64.3	325.4	187.8	5.38	6.20	5.94	2.75	2.72	2.79	Missing		39.4
	a	6	66.4	253.3	153.9	10.67	11.79	11.21	2.91	2.85	2.78	Missing		34.6
4	b	7	125.7	239.8	210.9	10.18	11.83	11.17	2.57	2.69	2.59	Missing		34.7
	c	4	38.0	158.9	91.9	10.76	11.23	11.05	2.73	2.68	2.80	Missing		34.8
	a	7	269.1	631.8	406.5	0.00	0.00	0.00	2.43	3.16	2.74	0.00	0.00	0.00
1	b	7	139.7	253.7	191.3	9.09	10.04	9.72	2.57	2.55	2.56	36.3	36.6	36.4
	c	9	265.2	432.8	329.3	4.74	5.98	5.28	2.64	2.61	2.57	39.3	40.5	39.8
	a	6	223.3	309.8	279.4	9.19	10.37	9.67	2.75	2.80	2.73	36.3	36.6	36.5
2	b	8	231.1	301.1	266.3	8.80	9.80	9.21	2.45	2.51	2.66	36.3	36.6	36.3
	c	6	219.8	296.8	258.1	9.46	10.22	9.68	2.74	2.72	2.69	35.7	36.9	36.3
	a	8	217.6	371.4	292.4	8.43	10.32	9.11	2.73	2.73	2.71	36.0	36.6	36.3
3	b	6	258.8	305.5	278.9	11.10	13.00	12.20	2.63	2.66	2.67	35.7	36.9	36.2
	c	7	236.8	308.2	274.7	9.70	11.53	10.66	2.81	2.78	2.83	35.4	37.2	36.5
	a	5	270.2	345.8	304.6	0.00	0.00	0.00	2.72	2.72	2.74	0.00	0.00	0.00
4	b	6	107.2	149.8	127.0	10.49	11.73	11.09	2.95	2.94	2.93	36.0	37.2	36.4
	c	6	166.7	221.7	188.7	6.99	8.35	7.50	2.87	2.83	2.84	38.4	39.3	39.0

Table 9-5: Part 2 Results - Less Dense Red Soil, Replicate 1

Position in Tank		No. of Observ-	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down	ations	min	max	mean	min	max	mean	start	end	mean	min	max	mean
	a	13	19.4	206.2	77.2	0.88	1.05	0.95	1.63	1.71	1.53	18.3	18.6	18.5
1	b	12	2.7	70.1	31.4	2.52	2.99	2.74	1.63	1.67	1.56	36.9	37.8	37.2
	c	14	47.8	100.0	70.8	1.22	1.52	1.33	1.64	1.60	1.61	12.3	12.6	12.4
	a	11	6.1	154.5	49.8	1.77	1.94	1.84	1.39	1.39	1.48	18.3	18.6	18.5
2	b	12	10.4	84.6	33.5	6.90	7.31	7.11	1.57	1.51	1.47	33.6	34.5	34.1
	c	15	49.5	147.0	92.3	0.87	0.93	0.91	1.62	1.62	1.57	12.3	12.9	12.5
	a		Missing			Missing			Missing			Missing		
3	b	14	30.1	131.7	72.0	1.02	1.37	1.20	1.45	1.48	1.54	12.3	12.6	12.6
	c	17	45.9	128.4	79.8	0.82	0.94	0.89	1.54	1.50	1.56	12.6	12.9	12.8
	a	9	16.3	141.3	63.1	0.56	0.68	0.64	1.61	1.66	1.52	18.9	19.2	19.0
4	b	16	32.0	54.0	42.0	1.65	1.70	1.67	1.50	1.50	1.56	18.6	18.6	18.6
	c	10	23.7	103.4	56.3	1.74	1.86	1.83	1.67	1.68	1.55	36.9	37.5	37.2
	a	12	0.0	68.3	27.8	3.72	5.37	4.66	1.84	1.86	1.55	36.6	37.8	37.0
5	b	13	33.0	89.3	57.2	0.80	1.86	1.21	1.55	1.56	1.57	18.3	18.6	18.4
	c	13	19.3	94.9	47.7	0.36	1.60	0.76	1.57	1.64	1.63	38.7	39.3	38.9
	a	16	10.0	118.5	46.3	1.04	1.28	1.18	1.49	1.55	1.50	12.6	13.2	12.9
6	b	16	2.9	174.6	63.0	0.58	0.81	0.70	1.72	1.72	1.48	12.9	13.2	13.0
	c	14	49.9	91.1	63.3	1.10	1.04	1.05	1.52	1.51	1.55	18.6	18.9	18.8
	a	9	4.1	196.5	62.8	0.77	0.83	0.79	1.43	1.42	1.45	12.9	13.2	13.0
7	b	13	9.6	120.9	47.5	2.79	2.96	2.86	1.70	1.74	1.57	37.8	38.4	38.2
	c	21	44.6	98.1	73.1	0.61	0.78	0.69	1.60	1.59	1.55	18.9	19.2	19.0
	a	16	0.0	345.0	46.6	5.50	6.32	5.99	1.88	1.95	1.37	35.4	37.8	36.2
8	b	16	19.2	136.0	64.2	1.18	1.54	1.37	1.25	1.27	1.50	12.6	12.9	12.8
	c	17	20.0	118.9	53.8	1.53	2.12	1.95	1.65	1.68	1.54	18.6	19.2	18.8

Table 9-5 : Continued - Replicate 2

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	10	25.8	152.2	71.0	2.00	2.39	2.15	1.55	1.51	1.49	13.8	14.1	13.8
1	b	19	0.9	65.4	29.3	2.13	2.30	2.20	1.51	1.52	1.49	40.2	41.1	40.8
	c	17	44.4	117.3	78.9	0.41	0.69	0.51	1.45	1.46	1.55	14.1	14.1	14.1
	a	13	0.7	241.1	40.3	5.00	5.68	5.22	1.46	1.42	1.33	38.7	39.9	39.3
2	b	14	45.3	79.7	60.8	0.50	0.67	0.56	1.51	1.52	1.56	20.4	20.7	20.6
	c	20	26.1	101.7	57.7	1.45	1.84	1.72	1.37	1.47	1.55	20.1	20.4	20.2
	a	10	1.2	98.7	41.7	1.87	2.15	2.01	1.56	1.57	1.53	41.1	41.1	41.1
3	b	17	39.5	93.1	67.2	0.08	0.30	0.23	1.58	1.59	1.58	14.1	14.4	14.2
	c	14	66.3	97.9	86.6	2.15	2.60	2.41	1.55	1.55	1.56	20.1	20.4	20.3
	a	11	18.6	84.5	66.0	1.74	2.14	1.93	1.52	1.53	1.57	13.5	14.1	13.8
4	b	21	17.9	92.1	42.2	5.49	5.94	5.74	1.45	1.48	1.47	38.4	39.6	38.9
	c	16	57.7	96.2	81.8	0.92	1.09	1.01	1.54	1.54	1.55	20.4	20.4	20.4
	a	9	58.9	159.2	97.9	1.51	2.30	1.77	1.58	1.55	1.56	13.8	14.1	13.9
5	b	13	23.4	55.0	36.0	2.44	2.66	2.52	1.54	1.55	1.61	40.5	40.8	40.6
	c	17	41.1	70.7	54.0	0.81	1.50	1.14	1.57	1.57	1.58	20.4	20.7	20.6
	a	13	29.1	211.8	83.5	0.38	4.13	0.77	1.41	1.45	1.53	14.1	15.0	14.2
6	b	17	30.6	102.1	58.5	0.43	0.54	0.46	1.46	1.48	1.54	20.4	20.7	20.6
	c	22	13.7	119.5	44.2	4.63	5.03	4.83	1.52	1.44	1.55	38.4	40.2	39.2
	a	16	22.7	85.9	59.9	0.47	0.86	0.60	1.47	1.49	1.54	14.1	14.4	14.2
7	b	18	11.0	75.6	34.6	1.91	2.02	1.98	1.53	1.51	1.57	40.2	40.5	40.4
	c	19	50.7	97.4	67.2	0.98	1.43	1.18	1.52	1.49	1.55	20.4	20.7	20.6
	a	21	6.6	104.1	39.0	6.74	7.74	7.15	1.58	1.58	1.51	36.6	37.2	36.9
8	b	13	36.6	80.6	56.5	0.56	0.73	0.61	1.52	1.51	1.61	20.7	21.0	20.8
	c	17	27.0	99.8	65.2	0.45	0.62	0.51	1.40	1.41	1.53	14.1	14.4	14.3

Table 9-5: Continued - Replicate 3

Position in Tank		No. of Observ-ations	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down		min	max	mean	min	max	mean	start	end	mean	min	max	mean
	a	16	0.5	164.0	47.1	4.03	5.66	5.33	1.57	1.62	1.52	35.7	40.5	39.4
1	b	21	42.1	127.3	82.8	1.10	1.66	1.44	1.56	1.56	1.58	20.4	20.7	20.5
	c	17	68.0	129.8	94.0	0.73	0.90	0.82	1.54	1.55	1.59	13.8	14.1	13.9
	a	15	2.4	146.6	44.6	2.62	2.73	2.69	1.36	1.41	1.52	40.2	40.5	40.3
2	b	15	34.4	93.4	62.6	0.86	1.03	0.93	1.49	1.50	1.53	20.7	21.0	20.8
	c	19	28.9	111.3	71.6	1.24	1.52	1.38	1.47	1.51	1.55	13.8	14.1	14.1
	a	16	3.6	124.5	36.1	1.64	1.92	1.78	1.40	1.41	1.48	38.7	39.6	39.0
3	b	20	26.9	80.4	50.1	1.07	1.18	1.10	1.60	1.56	1.58	20.7	21.0	21.0
	c	14	54.2	99.6	80.9	1.32	1.71	1.46	1.50	1.49	1.54	13.8	14.1	14.0
	a	12	34.4	108.6	68.4	0.66	0.72	0.67	1.59	1.61	1.54	14.4	14.7	14.4
4	b	18	50.0	76.1	62.8	0.80	0.85	0.82	1.57	1.58	1.60	20.7	21.0	21.0
	c	15	30.8	67.9	50.7	4.37	4.70	4.51	1.48	1.48	1.51	39.0	39.6	39.4
	a	12	24.2	79.1	57.2	1.18	1.34	1.27	1.43	1.46	1.54	20.4	20.7	20.6
5	b	19	33.2	97.8	66.3	0.34	0.50	0.45	1.55	1.55	1.58	13.8	14.1	14.0
	c	18	30.2	71.4	50.8	2.13	2.52	2.26	1.58	1.61	1.60	39.0	39.6	39.3
	a	12	36.3	92.7	61.4	0.47	0.53	0.50	1.57	1.58	1.53	20.4	20.7	20.6
6	b	25	12.7	55.3	32.8	4.09	4.59	4.41	1.44	1.45	1.51	38.1	39.6	39.4
	c	19	33.8	98.3	66.4	1.06	1.56	1.26	1.55	1.58	1.60	13.8	14.1	14.1
	a	12	32.2	69.3	46.5	0.36	0.47	0.43	1.47	1.48	1.53	20.7	21.0	20.8
7	b	19	33.2	81.3	57.9	0.40	0.46	0.41	1.52	1.52	1.56	21.0	21.3	21.0
	c	12	27.8	69.0	46.5	2.00	2.16	2.06	1.51	1.50	1.51	41.4	41.7	41.5
	a	18	12.4	145.6	58.9	0.44	0.55	0.48	1.44	1.47	1.51	14.4	14.7	14.5
8	b	22	18.5	72.1	52.9	0.52	0.74	0.61	1.50	1.51	1.59	14.1	14.4	14.3
	c	17	17.9	105.8	45.4	6.23	6.74	6.55	1.42	1.43	1.58	37.8	38.4	38.1

Table 9-6: Part 2 Results - Dense Red Soil,[1] Replicate 1

Position in Tank		No. of Observ-	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down	ations	min	max	mean	min	max	mean	start	end	mean	min	max	mean
	a	12			213.0			2.41			1.56			13.5
1	b	18			171.4			1.73			1.60			40.7
	c	14			146.6			1.15			1.57			20.6
	a	15			146.4			0.61			1.57			19.2
2	b	17			68.9			4.26			1.45			39.1
	c	14			93.6			0.55			1.56			13.8
	a	12			144.8			4.72			1.52			13.4
3	b	11			189.3			1.51			1.58			20.0
	c	13			206.0			3.06			1.52			19.4
	a	14			75.7			3.84			1.49			40.0
4	b	11			156.2			1.17			1.58			13.7
	c	10			109.2			1.80			1.57			39.8
	a	8			128.5			0.67			1.60			13.8
5	b	17			106.9			0.67			1.57			20.2
	c	16			86.6			1.17			1.58			40.6
	a	9			56.3			5.38			1.39			38.1
6	b	15			103.3			2.66			1.60			20.1
	c	14			149.5			0.96			1.54			13.5
	a	12			98.9			0.65			1.52			13.5
7	b	12			76.0			1.42			1.51			39.0
	c	13			75.0			1.90			1.60			20.0
	a	13			92.3			0.60			1.54			20.5
8	b	11			20.1			6.39			1.37			37.3
	c	18			120.8			1.66			1.55			13.1

1 only mean values are available

Table 9-6: Continued - Replicate 2

Position in Tank		No. of Observ-	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down	ations	min	max	mean	min	max	mean	start	end	mean	min	max	mean
1	a	10			141.0			0.96			1.61			13.7
	b	12			70.5			1.60			1.49			39.8
	c	13			84.9			1.28			1.56			20.2
2	a	6			100.5			0.82			1.51			20.3
	b	13			118.2			1.06			1.57			13.7
	c	8			68.4			4.18			1.38			38.5
3	a	6			124.8			1.24			1.47			20.2
	b	9			208.6			2.98			1.56			20.2
	c	11			90.7			1.34			1.54			40.3
4	a				74.5			4.97			1.37			39.8
	b	11			106.2			1.38			1.58			13.6
	c	10			96.9			0.62			1.63			14.0
5	a	5			171.8			2.55			1.53			13.4
	b	10			111.0			0.74			1.63			20.1
	c	9			102.4			0.94			1.58			13.8
6	a	8			104.1			4.42			1.48			40.3
	b	4			75.8			1.71			1.55			19.8
	c	11			100.2			1.81			1.58			39.3
7	a	11			92.3			0.89			1.55			20.2
	b	15			76.0			1.03			1.60			13.4
	c	10			106.2			0.24			1.53			13.3
8	a	12			27.7			7.38			1.41			38.2
	b	12			75.4			1.62			1.55			20.1
	c	10			75.4			1.83			1.48			39.6

Table 9-6: Continued - Replicate 3

Position in Tank		No. of Observ-	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down	ations	min	max	mean	min	max	mean	start	end	mean	min	max	mean
1	a	12			77.9			1.48			1.49			40.4
	b	12			112.2			2.73			1.55			20.0
	c	13			121.5			0.78			1.54			13.9
2	a	13			111.7			0.74			1.58			20.3
	b	15			126.5			1.96			1.55			13.7
	c	11			45.2			4.76			1.25			40.5
3	a	10			63.3			4.13			1.54			40.2
	b	12			82.7			0.22			1.59			14.0
	c	12			102.8			1.15			1.59			13.6
4	a	7			63.7			2.00			1.54			39.7
	b	10			95.5			0.70			1.61			20.6
	c	10			72.7			0.65			1.58			20.2
5	a	10			76.4			1.54			1.51			13.7
	b	13			45.4			4.69			1.54			40.0
	c	12			92.5			0.74			1.57			13.6
6	a	11			100.5			1.19			1.54			20.0
	b	9			68.9			1.73			1.61			40.9
	c	14			95.9			0.71			1.58			20.6
7	a	9			55.7			5.50			1.42			39.9
	b	13			76.3			0.51			1.62			14.0
	c	16			87.1			1.75			1.55			20.1
8	a	10			83.5			1.54			1.50			13.9
	b	10			53.2			1.08			1.62			20.7
	c	15			37.5			1.43			1.59			39.7

Table 9-7: Part 2 Results - Less Dense Brown Soil, Replicate 1

Position in Tank		No. of Observ-	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down	ations	min	max	mean	min	max	mean	start	end	mean	min	max	mean
	a	13	28.7	144.1	75.2	5.27	5.92	5.59	1.47	1.50	1.46	35.1	37.2	35.7
1	b	12	18.4	121.4	54.7	2.67	2.96	2.78	1.60	1.63	1.54	36.9	37.5	37.2
	c	12	58.3	96.7	77.4	1.25	1.48	1.35	1.50	1.56	1.55	12.3	12.9	12.5
	a	15	8.9	121.5	48.9	1.63	1.81	1.71	1.52	1.52	1.54	18.0	18.3	18.3
2	b	15	38.5	126.4	82.3	0.87	0.99	0.91	1.57	1.60	1.58	18.6	18.9	18.8
	c	14	74.2	120.9	93.5	0.90	1.01	0.96	1.66	1.65	1.64	12.6	12.9	12.7
	a	17	27.9	246.3	80.1	1.33	1.63	1.51	1.67	1.68	1.64	12.3	12.9	12.6
3	b	14	22.7	201.3	71.0	0.88	1.05	0.95	1.64	1.71	1.56	12.6	13.2	12.9
	c	14	52.2	130.5	82.9	1.86	2.15	1.95	1.56	1.56	1.57	18.3	18.6	18.5
	a	18	0.00	298.2	71.0	1.14	1.32	1.22	1.64	1.70	1.48	18.6	18.9	18.6
4	b	11	19.6	114.4	45.1	4.63	4.92	4.71	1.46	1.45	1.61	35.1	36.3	35.7
	c	18	22.0	155.3	60.9	1.38	1.62	1.51	1.54	1.54	1.56	37.2	37.5	37.4
	a	9	1.0	72.5	32.0	1.71	1.94	1.75	1.64	1.69	1.46	37.5	38.1	37.7
5	b	12	71.4	140.1	106.5	1.25	1.48	1.36	1.55	1.57	1.57	18.0	18.3	18.2
	c	11	62.1	132.1	94.5	0.56	0.85	0.73	1.62	1.64	1.61	12.6	12.9	12.7
	a	9	15.1	83.8	44.6	1.73	2.02	1.86	1.58	1.61	1.52	18.3	18.6	18.4
6	b	25	24.6	127.6	64.8	1.22	1.46	1.37	1.56	1.55	1.61	12.3	12.9	12.6
	c	17	34.1	108.3	59.7	5.58	6.11	5.95	1.64	1.63	1.60	34.8	36.9	35.5
	a	14	0.00	197.9	38.5	1.88	2.00	1.92	1.40	1.43	1.44	38.4	39.0	39.0
7	b	17	31.8	222.8	79.2	1.12	1.30	1.21	1.62	1.61	1.61	18.9	19.2	18.9
	c	16	60.8	118.5	78.2	1.74	2.15	1.95	1.65	1.64	1.60	19.2	19.5	19.4
	a	14	1.0	111.0	32.2	6.32	6.92	6.64	1.57	1.58	1.55	35.7	37.8	36.4
8	b	14	74.5	125.3	100.9	2.12	2.59	2.39	1.60	1.61	1.58	12.0	12.6	12.3
	c	13	58.4	123.0	84.6	0.75	0.93	0.83	1.55	1.58	1.56	12.9	13.2	12.9

Table 9-7: Continued - Replicate 2

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	13	23.4	63.2	44.0	0.74	1.13	1.02	1.50	1.54	1.54	20.4	20.7	20.4
1	b	21	12.6	45.5	30.4	2.58	2.81	2.68	1.46	1.51	1.53	40.8	41.1	40.9
	c	15	28.9	101.7	67.8	0.67	1.01	0.86	1.52	1.52	1.60	13.8	14.4	14.1
	a	16	0.00	119.0	31.7	4.93	5.72	5.47	1.61	1.50	1.43	39.0	39.6	39.0
2	b	17	17.0	88.5	66.9	1.22	1.95	1.72	1.51	1.26	1.54	18.9	20.4	20.2
	c	19	8.4	90.8	53.5	1.05	1.50	1.19	1.52	1.52	1.60	13.5	13.8	13.8
	a	13	24.0	96.9	51.6	0.58	0.69	0.62	1.45	1.46	1.51	14.1	14.4	14.3
3	b	15	25.7	69.6	46.4	1.64	1.97	1.80	1.52	1.51	1.52	20.1	20.7	20.4
	c	19	7.9	86.2	47.2	2.20	2.53	2.41	1.54	1.53	1.58	39.6	40.5	40.3
	a	11	29.2	81.4	50.3	0.57	0.69	0.62	1.53	1.55	1.56	20.4	20.4	20.4
4	b	17	36.8	117.8	65.4	1.25	1.97	1.51	1.54	1.56	1.57	13.5	14.1	13.9
	c	25	2.4	115.1	33.8	4.34	4.67	4.52	1.46	1.47	1.44	39.0	40.5	39.6
	a	15	62.7	125.9	85.8	1.93	2.94	2.30	1.50	1.51	1.57	13.5	14.1	13.8
5	b	18	17.7	63.1	39.2	2.20	2.48	2.33	1.49	1.52	1.56	39.6	39.9	39.8
	c	22	14.9	86.4	40.0	4.69	5.02	4.88	1.56	1.58	1.54	38.4	39.0	38.5
	a	14	1.0	226.4	57.5	0.34	0.68	0.49	1.41	1.38	1.56	13.2	14.7	14.4
6	b	17	15.8	59.7	42.9	1.05	1.44	1.22	1.48	1.50	1.58	19.8	20.7	20.6
	c	13	22.8	69.5	52.2	0.84	0.90	0.85	1.51	1.53	1.55	20.7	21.0	20.8
	a	16	16.5	33.0	23.9	4.83	5.45	5.15	1.47	1.49	1.48	38.7	39.6	39.1
7	b	15	7.7	75.1	34.8	2.70	3.04	2.82	1.47	1.49	1.55	Missing		
	c	24	7.4	73.3	50.4	0.92	1.26	1.10	1.44	1.46	1.58	20.7	21.3	21.0
	a	18	21.4	43.3	33.7	1.96	2.12	2.04	1.56	1.57	1.58	21.0	21.3	21.1
8	b	18	27.5	71.4	49.4	0.31	0.48	0.39	1.55	1.57	1.56	13.8	14.4	14.0
	c	19	9.2	61.5	48.2	0.79	1.02	0.90	1.59	1.60	1.63	13.8	14.1	14.1

Table 9-7: Continued - Replicate 3

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	13	40.9	102.8	70.6	0.86	0.97	0.93	1.56	1.56	1.53	20.4	20.7	20.5
1	b	18	37.6	107.7	72.9	1.14	1.59	1.42	1.58	1.57	1.54	13.5	13.8	13.7
	c	19	26.7	120.2	78.4	0.64	0.86	0.74	1.45	1.48	1.55	14.1	14.4	14.3
	a	14	16.3	68.5	33.3	5.52	6.13	5.90	1.50	1.52	1.45	37.8	38.4	38.0
2	b	14	28.8	55.0	38.4	2.01	2.17	2.11	1.61	1.57	1.57	40.2	40.5	40.4
	c	14	38.2	97.3	67.6	1.89	2.01	1.94	1.59	1.59	1.59	20.4	20.7	20.7
	a	11	31.6	103.0	51.6	0.47	0.58	0.51	1.51	1.50	1.56	14.1	14.4	14.3
3	b	20	30.0	86.3	48.5	0.78	0.84	0.81	1.58	1.58	1.55	20.7	21.0	21.0
	c	18	21.0	62.2	37.8	2.06	2.18	2.11	1.59	1.60	1.55	38.4	38.7	38.6
	a	23	15.7	63.8	36.4	1.21	1.49	1.38	1.58	1.59	1.54	21.0	21.3	21.1
4	b	15	18.7	73.6	38.3	4.49	5.05	4.87	1.61	1.61	1.54	38.4	39.3	38.8
	c	16	50.5	120.6	84.6	1.06	1.68	1.41	1.62	1.62	1.60	13.5	14.1	13.7
	a	16	4.4	48.4	25.4	4.42	5.38	4.86	1.44	1.47	1.44	39.0	40.2	39.5
5	b	19	25.7	104.0	62.8	0.71	1.10	0.92	1.46	1.50	1.53	13.8	14.1	14.0
	c	20	34.1	94.5	67.4	0.25	0.41	0.32	1.53	1.53	1.56	14.1	14.4	14.3
	a	20	2.7	90.7	35.2	0.99	1.16	1.06	1.63	1.63	1.59	20.4	20.7	20.5
6	b	24	6.0	54.1	33.0	1.24	1.57	1.38	1.55	1.55	1.52	38.7	39.9	39.3
	c	19	35.1	87.3	61.3	0.48	0.59	0.55	1.50	1.51	1.55	20.7	21.0	20.8
	a	12	29.9	98.6	56.3	0.15	0.20	0.18	1.63	1.64	1.59	14.1	14.4	14.4
7	b	18	23.8	67.7	45.3	0.49	0.66	0.57	1.63	1.63	1.60	14.1	14.4	14.3
	c	22	6.9	72.8	51.5	1.79	1.90	1.85	1.52	1.52	1.57	20.7	21.0	20.8
	a	19	5.5	83.8	27.8	2.60	2.82	2.71	1.48	1.51	1.55	38.4	39.6	38.7
8	b	21	17.2	88.6	43.1	0.35	0.46	0.38	1.55	1.54	1.54	20.7	21.0	20.8
	c	20	0.0	127.0	35.9	5.82	6.38	6.15	1.51	1.54	1.55	37.8	38.7	38.0

Table 9-8: Part 2 Results - Dense Brown Soil, Replicate 1

Position in Tank		No. of Observ-	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down	ations	min	max	mean	min	max	mean	start	end	mean	min	max	mean
	a	16	2.3	77.9	27.6	1.52	1.85	1.74	1.45	1.51	1.46	37.2	40.8	39.9
1	b	13	56.8	104.9	77.0	0.61	0.72	0.63	1.61	1.62	1.61	20.1	20.4	20.1
	c	17	3.9	79.5	33.9	5.51	7.36	7.01	1.47	1.47	1.39	33.3	39.6	38.2
	a	14	59.7	175.5	139.1	2.52	3.19	2.80	1.58	1.58	1.54	12.6	13.2	12.9
2	b	14	35.5	90.4	54.3	0.54	1.04	0.69	1.54	1.55	1.56	19.5	20.1	19.8
	c	17	15.8	88.6	64.4	0.36	0.59	0.51	1.63	1.63	1.62	13.5	14.1	13.8
	a	12	76.2	96.8	86.3	1.51	1.62	1.59	1.52	1.54	1.55	39.0	31.1	30.3
3	b	10	59.7	114.6	74.6	0.75	0.81	0.79	1.57	1.60	1.57	20.1	20.7	20.4
	c	20	54.0	89.7	71.7	1.59	1.93	1.75	1.54	1.55	1.55	19.8	20.1	20.0
	a	18	36.7	128.8	74.1	0.50	0.55	0.52	1.54	1.55	1.54	13.8	14.1	14.1
4	b	11	57.5	111.1	90.7	0.67	1.51	0.99	1.56	1.56	1.56	13.5	13.8	13.6
	c	14	38.5	85.2	53.9	3.81	4.20	3.99	1.51	1.49	1.55	33.9	40.5	38.5
	a	18	17.9	122.3	52.6	0.40	0.51	0.52	1.40	1.42	1.63	13.5	14.1	13.9
5	b	14	35.3	120.5	82.1	0.82	0.99	0.89	1.50	1.54	1.54	18.9	20.4	20.3
	c	17	25.7	104.0	48.2	3.66	4.16	3.84	1.61	1.62	1.44	38.7	40.5	39.7
	a	16	27.0	208.4	85.8	0.56	0.95	0.70	1.44	1.41	1.56	20.1	20.4	20.4
6	b	15	49.5	104.4	69.7	1.38	1.55	1.44	1.61	1.60	1.55	39.3	40.8	40.0
	c	17	37.7	133.9	86.3	0.44	0.78	0.62	1.61	1.61	1.61	13.8	14.4	13.9
	a	12	30.2	97.6	61.8	0.64	0.75	0.70	1.47	1.46	1.55	20.1	20.4	20.2
7	b	16	58.4	99.6	81.2	1.28	1.73	1.47	1.58	1.58	1.56	13.2	13.5	13.3
	c	14	54.4	119.0	76.6	0.27	0.50	0.40	1.57	1.57	1.56	13.5	13.8	13.8
	a	16	4.3	45.6	18.5	6.96	7.58	7.22	1.33	1.32	1.44	33.6	36.9	36.6
8	b	13	37.1	74.2	48.1	1.23	1.85	1.43	1.48	1.49	1.54	38.4	39.3	38.8
	c	14	23.4	118.2	73.4	1.58	2.70	2.15	1.61	1.62	1.62	20.1	20.7	20.4

Table 9-8: Continued - Replicate 2

Position in Tank		No. of Observ-ations	Draught lb			Torque (ft-lb)			Travel Rate (ft/s)			Frequency (cps)		
across	down		min	max	mean	min	max	mean	start	end	mean	min	max	mean
	a	13	84.0	121.1	111.0	0.91	1.08	1.02	1.56	1.50	1.54	20.1	20.4	20.3
1	b	18	36.1	96.6	68.0	1.57	1.85	1.68	1.46	1.46	1.46	39.0	41.4	40.2
	c	17	78.1	126.2	103.8	1.42	1.92	1.74	1.55	1.55	1.55	20.4	20.7	20.5
	a	11	71.2	108.3	85.5	1.25	1.59	1.42	1.55	1.56	1.56	13.5	13.8	13.7
2	b	12	41.5	119.8	66.7	3.39	3.90	3.62	1.54	1.55	1.48	39.0	39.9	39.4
	c	11	69.8	95.9	82.7	0.69	0.81	0.75	1.65	1.63	1.62	13.8	14.1	14.0
	a	10	66.0	208.8	118.6	0.58	0.86	0.74	1.35	1.37	1.55	20.1	20.4	20.3
3	b	15	68.4	116.5	100.9	1.79	2.30	2.01	1.58	1.60	1.60	19.8	20.1	20.1
	c	13	79.7	126.4	115.7	0.76	1.04	0.88	1.64	1.64	1.60	13.8	14.1	14.1
	a	9	36.9	205.9	91.8	1.52	1.69	1.61	1.66	1.66	1.59	40.2	43.2	41.3
4	b	13	20.8	89.5	37.3	5.77	6.10	6.00	1.52	1.51	1.45	38.4	40.8	38.9
	c	16	120.9	163.5	144.1	2.25	3.60	2.82	1.61	1.62	1.58	12.9	13.5	13.2
	a	10	44.4	110.4	74.1	0.60	0.76	0.69	1.58	1.57	1.53	20.1	20.4	20.1
5	b	10	64.6	114.0	79.4	1.54	1.60	1.57	1.54	1.53	1.55	39.6	41.1	40.4
	c	15	21.8	116.6	48.8	5.22	5.83	5.50	1.60	1.60	1.43	39.3	40.8	39.8
	a	11	71.0	127.3	101.7	1.25	2.04	1.59	1.52	1.54	1.54	13.2	13.8	13.5
6	b	16	76.9	129.2	95.1	0.73	1.01	0.85	1.57	1.57	1.55	13.5	13.8	13.8
	c	16	55.0	112.7	83.5	1.02	1.75	1.34	1.57	1.57	1.60	19.5	20.1	19.7
	a	12	34.8	143.4	78.4	1.62	1.85	1.72	1.51	1.52	1.52	19.8	20.1	20.0
7	b	15	41.2	115.4	69.3	0.02	0.36	0.19	1.57	1.56	1.55	13.5	13.8	13.5
	c	11	46.7	147.0	82.8	0.62	0.74	0.67	1.60	1.61	1.58	13.5	13.8	13.7
	a	7	8.2	64.6	33.0	2.71	3.16	2.97	1.50	1.50	1.38	38.1	39.3	38.6
8	b	16	50.2	80.4	64.6	0.76	0.87	0.79	1.56	1.56	1.54	20.4	20.4	20.4
	c	15	33.0	68.7	52.8	5.18	6.25	5.94	1.46	1.46	1.49	38.7	39.3	39.0

Table 9-8 : Continued - Replicate 3

Position in Tank across	down	No. of Observ-ations	Draught lb min	max	mean	Torque (ft-lb) min	max	mean	Travel Rate (ft/s) start	end	mean	Frequency (cps) min	max	mean
	a	10	25.6	120.4	67.6	0.75	0.92	0.79	1.56	1.56	1.51	13.8	14.1	14.0
1	b	12	75.4	155.1	111.6	1.55	2.45	2.01	1.54	1.54	1.56	13.2	13.8	13.5
	c	12	22.9	82.0	44.8	1.20	1.48	1.32	1.64	1.64	1.55	39.9	41.1	40.7
	a	9	41.2	52.2	45.8	0.91	1.25	1.08	1.54	1.54	1.55	20.4	20.7	20.5
2	b	15	19.6	63.5	34.6	4.50	5.17	4.88	1.43	1.43	1.41	38.7	41.1	39.7
	c	16	30.1	58.9	45.8	0.78	0.95	0.88	1.67	1.67	1.63	20.4	20.7	20.6
	a	13	48.1	240.4	108.9	0.54	1.10	0.80	1.57	1.56	1.57	13.8	14.1	13.9
3	b	14	59.5	93.9	77.8	1.23	1.62	1.44	1.51	1.51	1.55	20.1	20.7	20.3
	c	15	28.9	42.6	34.0	1.71	1.88	1.79	1.57	1.57	1.54	38.7	41.1	39.9
	a	20	0.0	242.0	52.2	0.12	0.85	0.61	1.55	1.56	1.46	13.8	14.4	13.9
4	b	9	31.3	104.1	57.7	0.30	0.36	0.33	1.67	1.67	1.62	20.4	20.7	20.5
	c	12	31.2	66.9	48.2	4.61	5.17	4.90	1.56	1.55	1.56	39.0	42.0	40.2
	a	12	12.4	180.0	38.8	1.18	1.51	1.37	1.54	1.50	1.60	39.6	41.7	40.4
5	b	10	56.3	149.8	101.4	0.62	1.07	0.89	1.57	1.60	1.55	13.2	13.5	13.4
	c	11	69.7	102.7	80.5	1.02	1.58	1.28	1.61	1.60	1.60	20.1	20.4	20.3
	a	12	29.9	89.0	63.6	0.43	0.66	0.58	1.70	1.70	1.64	13.8	14.1	14.0
6	b	7	20.6	53.6	34.0	5.77	5.99	5.92	1.41	1.41	1.48	39.3	40.8	39.9
	c	9	34.7	122.6	75.1	0.33	0.55	0.54	1.59	1.58	1.57	20.1	20.4	20.2
	a	12	5.1	128.8	38.4	4.94	5.61	5.21	1.25	1.26	1.54	38.4	40.5	39.2
7	b	17	32.1	95.3	48.1	0.02	0.30	0.18	1.46	1.46	1.57	14.1	14.4	14.2
	c	14	32.7	84.9	55.4	1.60	1.83	1.69	1.51	1.51	1.57	39.6	41.4	40.4
	a	14	15.5	268.3	74.4	0.54	1.04	0.72	1.24	1.25	1.56	13.5	13.8	13.6
8	b	18	23.8	133.7	63.4	0.33	0.55	0.45	1.55	1.56	1.53	20.4	20.7	20.6
	c	13	38.3	78.1	48.0	1.03	1.48	1.16	1.57	1.56	1.57	20.4	20.7	20.4

Table 9-9: Drawbar and Total Horsepower of the Vertical Wedge - Part 1.

Repli-cate	Position in tank Down	a DHP	a THP	a THP[1]	b DHP	b THP	b THP[1]	c DHP	c THP	c THP[1]
					Across					
Less Dense Red Soil										
1	1	0.431	3.269		0.456	3.409		0.442	3.560	
	2	0.624	0.624	0.624	0.312	3.101	2.594	0.432	1.884	1.538
	3	0.703	0.703	0.703	0.341	3.148	2.638	0.481	1.538	1.286
	4	0.306	3.589		0.282	3.682		0.290	3.660	
2	1	0.785	0.785	0.785	0.273	4.213	3.498	0.413	2.572	2.057
	2	0.623	4.286		0.533	3.611		0.499	3.538	
	3	0.490	3.503		0.455	3.575		0.542	3.735	
	4	0.747	0.747	0.747	0.300	3.379	2.820	0.529	2.891	2.327
Dense Red Soil										
1	1	0.537	4.381		1.023	4.819		0.650	4.611	
	2	2.479	2.479	2.479	2.213	6.595	5.801	1.488	3.948	3.365
	3	2.967	2.967	2.967	2.241	6.131	5.966	2.231	4.697	4.573
	4	1.317	5.660		1.422	5.770		1.481	5.950	
2	1	2.948	2.948	2.948	1.856	6.275	5.464	2.201	4.936	4.283
	2	1.350	5.296		1.848	5.809		1.044	4.954	
	3	1.655	6.014		1.636	6.328		1.749	6.496	
	4	1.617	1.617	1.617	0.862	4.810	4.089	1.042	3.275	2.744
Less Dense Brown Soil										
1	1	0.526	3.422		0.458	3.687		0.366	3.170	
	2	0.837	0.837	0.837	0.506	3.246	2.748	0.632	2.033	1.698
	3	0.825	0.825	0.825	0.428	3.343	2.814	0.464	1.592	1.323
	4	0.255	3.858		0.263	3.599		0.335	3.582	
2	1	0.615	0.615	0.615	0.321	4.274	3.556	0.478	4.152	3.275
	2	0.338	3.402		0.470	3.705		0.515	3.873	
	3	0.358	2.787		0.633	4.330		0.623	4.272	
	4	0.928	0.928	0.928	0.381	3.794	3.175	0.635	2.585	2.120
Dense Brown Soil										
1	1	0.816	4.837		0.573	4.962		0.855	5.228	
	2	2.332	2.332	2.332	1.415	5.520	4.782	1.381	3.860	3.257
	3	2.054	2.054	2.054	0.994	4.970	4.262	0.956	3.630	2.990
	4	0.777	5.210		0.997	5.420		0.467	4.850	
2	1	2.031	2.031	2.031	0.891	4.935	4.200	1.537	3.937	3.365
	2	1.386	5.420		1.288	5.111		1.262	5.277	
	3	1.440	5.223		1.352	6.413		1.412	5.860	
	4	1.514	1.514	1.514	0.676	5.283	4.445	0.976	4.313	3.516

1 adjusted for drive friction

Table 9-10: Contribution Coefficients to the Variance of the Observations.

						Replicate 1(2)						
Blocks		1(2)				2(1)			3(4)		4(3)	
Without Order of Tillage												
m:	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12
a_0:	0	0	0	5/12	-1/3	-1/12	5/12	-1/3	-1/12	0	0	0
a_1:	0	0	0	-1/12	1/6	-1/12	-1/12	1/6	-1/12	0	0	0
a_2:	0	0	0	-1/12	-1/3	5/12	-1/12	-1/3	5/12	0	0	0
b_1:	1/4	1/4	1/4	0	-1/4	0	0	-1/4	0	-1/12	-1/12	-1/12
b_2:	-1/12	-1/12	-1/12	1/6	5/12	1/6	-1/6	1/12	-1/6	-1/12	-1/12	-1/12
b_3:	-1/12	-1/12	-1/12	-1/6	1/12	-1/6	1/6	5/12	1/6	-1/12	-1/12	-1/12
b_4:	-1/12	-1/12	-1/12	0	-1/4	0	0	-1/4	0	1/4	1/4	1/4
With Order of Tillage												
m:	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12	1/12
a_0:	-5/12	1/3	1/12	5/12	-1/3	-1/12	5/12	-1/3	-1/12	-5/12	1/3	1/12
a_1:	1/12	-1/6	1/12	-1/12	1/6	-1/12	-1/12	1/6	-1/12	1/12	-1/6	1/12
a_2:	1/12	1/3	-5/12	-1/12	-1/3	5/12	-1/12	-1/3	5/12	1/12	1/3	-5/12
b_1:	1/6	5/12	1/6	0	-1/4	0	0	-1/4	0	-1/6	1/12	-1/6
b_2:	0	-1/4	0	1/6	5/12	1/6	-1/6	1/12	-1/6	0	-1/4	0
b_3:	0	-1/4	0	-1/6	1/12	-1/6	1/6	5/12	1/6	0	-1/4	0
b_4:	-1/6	1/12	-1/6	0	-1/4	0	0	-1/4	0	1/6	5/12	1/6
o_1:	1/3	-1/6	-1/6	0	0	0	0	0	0	1/3	-1/6	-1/6
o_2:	-1/6	1/3	-1/6	0	0	0	0	0	0	-1/6	1/3	-1/6
o_3:	-1/6	-1/6	1/3	0	0	0	0	0	0	-1/6	-1/6	1/3

Table 9-11: Draught of the Horizontal Share

Soil		Less Dense Red		Dense Red		Less Dense Brown		Dense Brown	
Nominal Amplitude (ft)		0.010	0.020	0.010	0.020	0.010	0.020	0.010	0.020
Frequency (cps)	Rake Angle/Draught (degrees)								
12-1/2	0	73.7	72.6	105.1	112.6	68.1	72.9	71.2	98.7
	20	73.0	64.1	107.2	139.4	69.2	67.4	89.8	87.0
18-3/4	0	64.2	62.8	109.0	115.7	67.5	52.9	70.5	76.0
	20	65.6	54.7	111.0	108.9	59.1	52.9	80.4	74.7
37-1/2	0	45.3	41.0	89.1	58.8	30.6	46.7	55.2	37.9
	20	38.5	39.3	82.2	58.8	48.5	32.4	57.7	48.0
	Plane of Osc./Draught								
12-1/2	Horizontal	76.8	61.5	117.4	110.1	63.4	60.9	78.8	72.2
	Tilted	69.9	75.1	94.9	142.0	73.8	79.4	82.2	113.5
18-3/4	Horizontal	66.8	52.4	115.4	89.6	61.9	40.2	76.0	70.1
	Tilted	63.0	65.1	104.6	135.0	64.7	65.6	75.0	80.5
37-1/2	Horizontal	47.3	39.5	84.6	59.3	37.7	34.9	52.4	35.2
	Tilted	36.4	40.8	86.7	58.3	41.4	44.2	60.4	50.7
	Standard Error	3.87		10.30		3.68		4.78	

Table 9-12: Drawbar Horsepower of the Horizontal Share

Soil		Less Dense Red		Dense Red		Less Dense Red		Dense Brown	
Nominal Amplitude (ft)		0.010	0.020	0.010	0.020	0.010	0.020	0.010	0.020
Frequency (cps)	Rake Angle/ (degrees)	DHP							
12-1/2	0	0.210	0.203	0.295	0.318	0.199	0.206	0.204	0.281
	20	0.202	0.182	0.312	0.393	0.194	0.197	0.259	0.245
18-3/4	0	0.181	0.179	0.315	0.330	0.170	0.151	0.202	0.217
	20	0.185	0.154	0.314	0.306	0.167	0.149	0.226	0.213
37-1/2	0	0.128	0.113	0.255	0.153	0.083	0.130	0.153	0.103
	20	0.109	0.103	0.231	0.153	0.140	0.087	0.163	0.128
	Plane of Osc./ Draught								
12-1/2	Horizontal	0.216	0.175	0.336	0.311	0.176	0.177	0.225	0.206
	Tilted	0.196	0.210	0.271	0.400	0.216	0.226	0.238	0.320
18-3/4	Horizontal	0.188	0.148	0.329	0.255	0.154	0.113	0.216	0.200
	Tilted	0.177	0.184	0.299	0.380	0.183	0.188	0.213	0.230
37-1/2	Horizontal	0.134	0.105	0.242	0.152	0.105	0.097	0.145	0.090
	Tilted	0.103	0.111	0.244	0.154	0.117	0.120	0.171	0.140
Standard Error		0.0116		0.0291		0.0119		0.0135	

Table 9-13: Torque of the Horizontal Share

Soil		Less Dense Red		Dense Red		Less Dense Red		Dense Brown	
Nominal Amplitude (ft)		0.010	0.020	0.010	0.020	0.010	0.020	0.010	0.020
Frequency (cps)	Rake Angle/ DHP (degrees)								
12-1/2	0	0.274	0.984	0.322	0.958	0.432	1.064	0.333	1.041
	20	0.474	0.963	0.438	1.290	0.303	0.958	0.372	0.869
18-3/4	0	0.382	0.887	0.443	1.086	0.475	0.997	0.360	0.720
	20	0.387	0.889	0.510	1.177	0.502	1.099	0.375	1.025
37-1/2	0	0.887	4.186	0.820	3.370	0.990	3,522	0.816	3.893
	20	1.287	3.292	0.857	3.415	1.257	3.743	0.934	3.361
	Plane of Osc./ **THP**								
12-1/2	Horizontal	0.444	0.814	0.434	1.097	0.470	0.708	0.370	0.063
	Tilted	0.304	1.134	0.327	1.151	0.266	1.314	0.335	1.307
18-3/4	Horizontal	0.430	0.884	0.576	0.964	0.431	1.016	0.445	0.830
	Tilted	0.339	0.891	0.377	1.299	0.545	1.081	0.290	0.915
37-1/2	Horizontal	1.125	3.528	0.916	3.903	1.166	3.587	1.003	3.770
	Tilted	1.050	3.950	0.760	2.882	1.081	3.679	0.746	3.484
Standard Error		0.1174		0.1587		0.0988		0.1464	

Table 9-14: Shaft Horsepower of the Horizontal Share

Soil		Less Dense Red		Dense Red		Less Dense Brown		Dense Brown	
Nominal Amplitude (ft)		0.010	0.020	0.010	0.020	0.010	0.020	0.010	0.020
Frequency (cps)	Rake Angle/ DHP (degrees)								
12-1/2	0	0.0223	0.1725	0.0431	0.1571	0.0812	0.1461	0.0684	0.1424
	20	0.0936	0.1287	0.0763	0.1906	0.0325	0.1610	0.0436	0.1497
18-3/4	0	0.0962	0.1910	0.0965	0.2549	0.0968	0.2347	0.0802	0.1698
	20	0.0793	0.2102	0.1254	0.2605	0.1237	0.2438	0.0904	0.2330
37-1/2	0	0.4112	1.7674	0.3740	1.5166	0.4604	1.5103	0.3764	1.7151
	20	0.5714	1.4730	0.3910	1.5215	0.5158	1.6244	0.4220	1.5159
Plane of Osc./ THP									
12-1/2	Horizontal	0.0677	0.1268	0.0762	0.1620	0.0921	0.0884	0.0514	0.1016
	Tilted	0.0483	0.1743	0.0431	0.1857	0.0216	0.2188	0.0606	0.1906
18-3/4	Horizontal	0.0990	0.1987	0.1322	0.2222	0.0846	0.2432	0.1093	0.1845
	Tilted	0.0765	0.2025	0.0896	0.2931	0.1359	0.2353	0.0613	0.2183
37-12	Horizontal	0.5003	1.5331	0.4238	1.7264	0.5264	1.5523	0.4519	1.6802
	Tilted	0.4824	1.7074	0.3412	1.3118	0.4498	1.5824	0.3464	1.5508
Standard Error		0.03768		0.04677		0.03372		0.05631	

Table 9-15: Total Horsepower of the Horizontal Share

Soil		Less Dense Red		Dense Red		Less Dense Brown		Dense Brown	
Nominal Amplitude (ft)		0.010	0.020	0.010	0.020	0.010	0.020	0.010	0.020
Frequency (cps)	Rake Angle/ (degrees)	THP							
12-1/2	0	0.2322	0.3839	0.3384	0.4748	0.2712	0.3562	0.2725	0.4229
	20	0.2959	0.3111	0.3881	0.5844	0.2302	0.3548	0.3023	0.3950
18-3/4	0	0.2764	0.3707	0.4103	0.5849	0.2889	0.3865	0.2823	0.3866
	20	0.2646	0.3631	0.4396	0.5746	0.2911	0.3934	0.3171	0.4465
37-1/2	0	0.5383	1.8809	0.6287	1.6700	0.5452	1.6388	0.5293	1.8179
	20	0.6812	1.5752	0.6222	1.6762	0.6503	1.7134	0.5854	1.6438
	Plane of Osc./	THP							
12-1/2	Horizontal	0.2838	0.3019	0.4121	0.4734	0.2644	0.2650	0.2762	0.3079
	Tilted	0.2444	0.3931	0.3144	0.5857	0.2370	0.4460	0.2986	0.5100
18-3/4	Horizontal	0.2856	0.3488	0.4616	0.4778	0.2609	0.3553	0.3252	0.3846
	Tilted	0.2554	0.3851	0.3883	0.6717	0.3191	0.4246	0.2743	0.4486
37-1/2	Horizontal	0.6353	1.6372	0.6658	1.8803	0.6328	1.6485	0.5971	1.7704
	Tilted	0.5842	1.8188	0.5850	1.4658	0.5628	1.7036	0.5176	1.6912
Standard Error		0.03800		0.06232		0.03743		0.05571	